Economy-Wide Modeling: Social Cost and Welfare White Paper

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Prepared for the U.S. EPA Science Advisory Board Panel on Economy-Wide Modeling of the Benefits and Costs of Environmental Regulation

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1. Introduction

Executive Order 12866 advises each agency to "assess both the costs and the benefits of the intended regulation and, recognizing that some costs and benefits are difficult to quantify, propose or adopt a regulation only upon a reasoned determination that the benefits of the intended regulation justify its costs." In addition, it directs agencies to "select those approaches that maximize net benefits (including potential economic, environmental, public health and safety, and other advantages; distributive impacts; and equity), unless a statute requires another regulatory approach." This objective, that a policy's net benefits be positive, is referred to as the Potential Pareto criterion.

This white paper is focused primarily on assessing when an economy-wide model may be the most appropriate tool for estimating the costs of proposed air regulations for use in ex-ante benefit-cost analysis (BCA). Assessing when and how to incorporate benefits of proposed air regulations into economy-wide models is discussed in a companion white paper on benefits estimation, "Economy-Wide Modeling: Benefits of Air Quality Improvements" (from here forward, referred to as the benefits white paper). This dichotomy of the discussion is for the purpose of tractability and is not meant to imply that the estimation of benefits and costs are necessarily independent of each other.

According to the EPA's *Guidelines for Preparing Economic Analyses* (from here forward, referred to as EPA's Economic Guidelines), "in conducting a BCA, the correct measure to use is the social cost" (U.S. EPA, 2010a). Social cost represents the total burden that a regulation will impose on the economy. It is defined as the sum of all opportunity costs incurred as a result of a regulation, where an opportunity cost is the value lost to society of all the goods and services that will not be produced and consumed in the presence of regulation as resources are reallocated away from consumption and production activities towards pollution abatement. To be complete, an estimate of social cost should include both the opportunity cost of current consumption that will be foregone as a result of the regulation, and the loss that may result if the regulation reduces capital investment and thus future consumption.

The imposition of a new regulation on firms raises their production costs. Each unit of output is more costly to produce than before because of expenditures incurred to comply with the regulation, referred to as compliance costs. For the industry, this is represented as an upward shift in the supply curve, which (assuming an unchanging and downward-sloping demand schedule) results in a higher equilibrium price and causes a reduction in consumption of the good.

When impacts outside of the regulated sector are not expected to be significant, the social cost of the regulation can be approximated by the sum of compliance costs (the white area in Figure 1) and the opportunity cost of the reduction in output (the black triangle in Figure 1) in the directly affected market, assuming few transition costs. Together, these two effects are captured by measuring the change in consumer and producer surplus in that market after the regulation compared to before it is in place.

Figure 1. Effects of a Regulation on a Directly Regulated Competitive Market
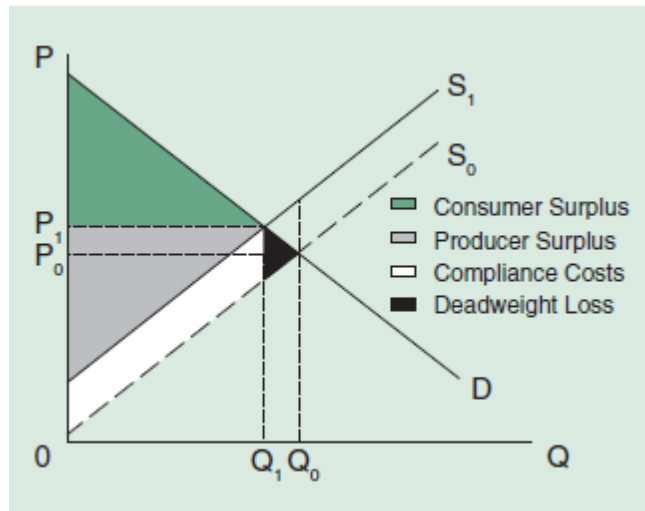
However, when many sectors are expected to experience significant impacts due to the regulation, either directly or indirectly, a BCA that focuses only on effects in the directly regulated sector may substantially misestimate the social cost of the regulation. Kokoski and Smith (1987) suggest that, even for relatively small multi-sector policy shocks, partial equilibrium approaches result in large errors in welfare estimation. Hazilla and Kopp (1990) note the importance of secondary effects in sectors facing no regulatory requirements under the Clean Air or Water Acts. Pizer et al. (2006) find that pre-existing tax distortions result in a significant divergence between partial and general equilibrium estimates of economic welfare costs from carbon pricing policies for the commercial building, industrial, transportation, and electricity sectors. Thus, as stated by Hahn and Hird (1990), a key question is: when is it reasonable to assume away these "second-order effects?" They note the difficulty in answering this question as it likely varies across industries and regulations.

It is also important to note that benefit-cost analyses of air regulations typically focus on long-run effects.[1] Compliance costs are treated as permanent additions to the cost of production for a firm, while effects in other sectors outside of those directly regulated by the EPA are incurred once the economy adjusts to a new equilibrium (e.g., in response to changes in prices that result from additional compliance expenditures incurred in the regulated sectors). However, it is possible in some contexts that firms and/or consumers incur additional short-term costs during the period when the economy is adjusting to the new equilibrium (i.e., transition or adjustment costs – see Box 1). Examples include costs to train workers to use new equipment, search costs as some workers seek employment in other sectors, and additional costs associated with initially limited availability of new monitoring or abatement equipment. It is also possible that at least some factors of production are fixed initially, limiting the ability of firms to respond quickly to new regulatory requirements. For instance, contractual or technological constraints may prevent firms

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[1] Regulatory options are "modeled as economic changes that move the economy from a state of equilibrium absent the regulation (the baseline) to a new state of equilibrium with the regulation in effect" (U.S. EPA, 2010a).

from fully adjusting their input mix or output decisions until those contracts expire or technology is ready to be replaced.[2] If these types of adjustment costs are substantial, sole focus on long run costs may underestimate the total social cost of regulation.

It is in this context that we discuss an analyst's choice of models and, in particular, when an economy-wide or general equilibrium (GE) approach to evaluate the social cost of regulatory policy adds significant value. This white paper documents the steps involved, key assumptions, and challenges that may arise when estimating the social cost of an air regulation using a computable general equilibrium (CGE) model. In particular, section 2 reviews how the EPA typically estimates the social cost of an air regulation, ranging from engineering to partial equilibrium to general equilibrium approaches. Section 3 gives an overview of air regulations and discusses potential challenges in representing them in a CGE framework. Sections 4 and 5 describe how the choice of model may be affected by particular attributes of an air regulation and the structure and assumptions underlying a CGE model, respectively. Section 6 discusses potential metrics for measuring social cost and briefly describes available U.S. CGE models. Section 7 discusses linking CGE models with detailed sector models and the practical challenges EPA has encountered when attempting to link models in the past. Finally, section 8 offers concluding remarks.

2. Overview of Social Cost Framework in a Regulatory Setting

This section describes the basic aspects of BCA as conducted by the EPA to estimate the social costs of air quality regulations, including the distinction between social costs and compliance costs, existing guidance on the choice of modeling approach, and how social costs of air regulations are typically analyzed by the EPA, ranging from engineering to partial equilibrium to general equilibrium approaches.

2.1 Benefit-Cost Analysis for Air Quality Regulations

The EPA conducts benefit-cost analysis for all rules deemed economically significant or particularly novel. Economically significant rules are defined by Executive Order 12866 as those with costs and/or benefits of at least $100 million (nominal) in a single year. The purpose of the BCA is to inform the policy process by quantifying the expected social benefits and costs of alternative regulatory options relative to a baseline representation of what is expected to occur in the absence of the regulation. The Office of Management and Budget (OMB) advises agencies to account for the following, "where relevant, in their analysis and provide estimates of their monetary values: private-sector compliance costs and savings; government administrative costs and savings; gains or losses in consumers' or producers' surpluses; discomfort or inconvenience benefits and costs; and gains or losses of time in work, leisure, and/or commuting/travel settings" (OMB, 2003).

In addition to challenges related to specifying the baseline, analysts may have to grapple with substantial uncertainty when estimating social costs: for example, in identifying affected entities, the methods of compliance they may pursue, the expenditures associated with possible control strategies, and whether

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[2] Smith (2015) refers to adjustment costs as "resource re-allocations that arise from unanticipated shocks." Note that many EPA regulations are phased in over time in an attempt to reduce these costs.

costs borne by firms in one sector will result in notable price changes that could affect sectors not subject to the regulation. Another key challenge for the EPA when conducting analysis is the complex structure of most regulations compared to the market-based policies that are primarily considered by the economics literature. One common form of air quality regulation is an emissions rate standard that is met by a facility or sub-unit of a facility (e.g., a boiler), where affected entities have discretion with regard to the compliance method they use to achieve the standard. Another type of air regulation is a standard on either the rate of emissions of a particular product when in use (e.g., lawnmowers, boat engines) or on the product content that applies to the manufacturer. Often standards in air regulations are differentiated by vintage, such that new and existing facilities or products are treated differently. Standards may be further differentiated by fuel type, industrial process, product, or other factors associated with the degree to which certain entities contribute to a particular air pollution problem or the cost of abatement. Section 3 of this paper discusses the nuances of U.S. air quality regulations in greater detail.

When attempting to measure social cost, analysts consider what analytic approaches to pursue. Depending on the scope of the regulation and the information and resources available, engineering, partial and/or general equilibrium economic frameworks may be employed. Examples of specific models used by the EPA to estimate costs are described in the Appendix.

2.2 Engineering and Partial Equilibrium Approaches to Estimating Cost

An engineering approach to estimating costs estimates direct compliance expenditures from adopting a particular technology or process (i.e., capital costs, operating and maintenance costs, administrative costs) by an individual emitting unit or facility conditional on a given level of output. It does not attempt to estimate welfares impacts associated with a change in production or use of inputs. Its primary advantage is the ability to generate highly detailed and, when data are available, fairly precise information on compliance options and their associated costs that reflect the heterogeneity of regulated entities. The importance of this detailed information cannot be overemphasized, as key stakeholders are keenly interested in understanding compliance pathways and the anticipated burden associated with a regulation. A key question for analysts and decision-makers is whether it is worth expending additional resources to expand beyond an engineering cost approach to capture other substantial costs either to the industry itself, to related industries, or to the economy as a whole.

Engineering analyses typically do not account for producer or consumer behavioral change that may be incentivized by the regulation. For example, to the extent that producers respond to the regulation by adjusting inputs or processes because this represents a cheaper method of compliance, relative to the technologies considered in the engineering analysis, they will incur a lower compliance cost than estimated using the engineering analysis. If the regulation increases the cost of production, which is then passed onto consumers in the form of higher prices, an engineering analysis also misses the demand response. (The degree to which a demand response influences cost depends on the price elasticity of demand for output of the regulated sector and the degree of competition in the market.) Likewise, an engineering approach does not capture supply side responses such as changes in the composition of goods produced by the industry or changes in product quality.

A partial equilibrium economic model captures both supply and demand responses in the regulated sector and may be extended to consider a small number of related sectors (e.g., upstream markets that supply intermediate goods to the regulated sector, or markets for substitute or complimentary products). According to the EPA's Economic Guidelines, "partial equilibrium analysis is usually appropriate when the scope of a regulation is limited to a single sector, or to a small number of sectors….The use of partial equilibrium analysis assumes that the effects of the regulation on all other markets will be minimal and can either be ignored or estimated without employing a model of the entire economy" (U.S. EPA 2010a). When these assumptions are valid, a partial equilibrium measure may adequately capture the social cost of a regulation. In contrast to an engineering analysis, a partial equilibrium analysis may derive a more complete measure of social cost because it takes into account behavioral change (i.e., it is equivalent to a measure of the net change in consumer and producer surplus relative to the pre-regulatory equilibrium).

Box 1. Cost Concepts and Definitions

Compliance costs: Costs firms incur to reduce or prevent pollution in order to comply with the regulation; the two main components are capital costs and operating costs. Capital costs are often one-time costs related to the installation or retrofit of structures or equipment to reduce emissions; operating costs are reoccurring annual expenditures associated with the operation and maintenance of the equipment.

Social cost: The total burden that a regulation will impose on the economy. It is defined as the sum of all opportunity costs incurred as a result of a regulation, where an opportunity cost is the value lost to society of all the goods and services that will not be produced and consumed in the presence of regulation as resources are reallocated towards pollution abatement.

Direct costs: Costs that fall directly on regulated entities as a result of the regulation (often synonymous with compliance costs)

Indirect costs: Costs incurred in related markets or experienced by consumers or government not under the direct scope of the regulation; often transmitted through changes in prices of the goods or services produced in the regulated sector

Transition costs: Short term costs incurred only during the time period when the economy is still adjusting to a new equilibrium

Interaction effects: How changes in prices or quantities in one sector interact with other sectors to cause effects in other markets

Feedback effects: When changes in other sectors feedback to the regulated sector and cause additional behavioral effects (e.g., requirements to install a scrubber could drive up the price of scrubbers which then, in turn, increases compliance costs in the regulated sector)

Source: U.S. EPA (2010a)

2.3 General Equilibrium Approaches to Estimating Cost

When a large number of sectors are expected to experience significant impacts as the result of a regulation, either directly or indirectly, such that the effects are spread more broadly throughout the economy, a general equilibrium approach may more adequately measure social cost. Likewise, a large regulatory change in a single sector may have indirect effects on a myriad of other markets. The EPA's Economic Guidelines notes that "in such cases, a general equilibrium framework, which captures linkages between markets across the entire economy, may be a more appropriate choice" (U.S. EPA, 2010a).

The EPA's Economic Guidelines provide the example of a regulation that imposes emission limits on the electric utility sector. Compliance costs are passed along as electricity price increases. Because electricity is used as an input in the production of many goods, the prices of these products may also increase reflecting the increase in their marginal cost of production. Households are affected through two channels: as consumers of these goods, and as direct consumers of electricity. Increases in prices may cause households to alter their choices in terms of both relative consumption of energy-intensive goods and services and also the number of hours they are willing to work. The impacts of a regulation also may interact with pre-existing distortions in other markets, which may cause additional impacts on welfare.[3] In cases such as these, a general equilibrium approach is capable of identifying the direct and indirect impacts of policy as its effects flow through the economy, including changes in substitution among factors of production, trade patterns, endogenous demands, and even inter-temporal consumption. These effects of compliance with a regulation are partially or wholly missed by engineering or partial equilibrium approaches (Table 1 summarizes the types of costs typically captured by engineering, partial equilibrium, and economy-wide models used by the EPA to analyze air regulations).

Table 1. Types of Costs Captured by Main EPA Model Types

Attributes	Engineering Approach	Partial Equilibrium	CGE
Can estimate welfare effects (social cost)			√
Can measure direct compliance costs	√	Sometimes	
Can measure transition costs	√	√	
Can capture indirect effects			√
Can capture feedback and interaction effects			√

Source: U.S. EPA (2010a)

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[3] For example, pre-existing distortions in the labor market (e.g., the choice between the number of hours an individual works versus how much leisure he or she takes, which is defined as any time spent on activities that do not earn a wage, is already distorted due to income taxes that tax labor but not leisure) may be alleviated or exacerbated by an implicit change in the real wage due to the imposition of a regulation.

Another example is provided in the analysis of the benefits and costs of the Clean Air Act Amendments (CAAA) from 1990 to 2020 (U.S. EPA, 2011a). In the cost-only scenario (i.e., no benefits are included) the EPA found that the total estimated reduction in GDP due to the CAAA was 50 to 70 percent larger than the direct compliance cost estimates for 2010 and 2020, respectively. It attributes this difference to "secondary effects of compliance costs on the overall economy, a large portion of which are likely the result of increases in energy prices, which have broad effects on overall production. Another factor is that investment in pollution control capital can divert capital from the purpose of enhancing long-term productivity within the industrial sector."

Pizer and Kopp (2005) characterize the choice of method for estimating costs as related to the types of costs we anticipate will result from the policy – direct compliance costs, foregone opportunities, lost flexibility, etc. – as well as the degree to which the policy will "meaningfully influence" the prices of goods and services. When a regulation is expected to influence prices, an analyst needs to consider potential welfare consequences due to pre-existing distortions in other markets and other general equilibrium effects such as changes in terms of trade, among others.[4] For instance, if an environmental regulation affects wages such that individuals opt to work fewer hours, this exacerbates an already existing distortion in the labor market, since labor taxes already discourage individuals from working as much as they would otherwise, and has a welfare cost not captured by direct compliance cost estimates.

To help clarify when a general equilibrium approach is warranted, Pizer and Kopp define the cost of regulation as:

$$C_i\ (a,\ z)$$

where a is a function of a vector of parameters describing the environmental regulation, and z is a vector of parameters summarizing the current economic equilibrium (e.g., input prices and output levels for a firm, prices and income for a consumer) for agent i. When z is fixed and i is limited to the agents that are directly regulated, then a partial equilibrium estimation approach adequately captures the cost of regulation. However, when z is endogenous and the affected agents go beyond the regulated sector, a general equilibrium approach is needed to capture price and output changes in other markets.

The most common approach to estimating the social cost of a regulation in a general equilibrium setting is the use of a computable general equilibrium (CGE) model. CGE models assume that for some discrete period of time an economy can be characterized by a set of conditions in which supply equals demand in all markets. When the imposition of a regulation alters conditions in one market, a general equilibrium model determines a new set of relative prices for all markets that return the economy to its long-run equilibrium. These prices in turn determine changes in sector outputs and household consumption of goods, services, and leisure in the new equilibrium. In addition, the model determines a new set of relative prices and demand for factors of production (e.g., labor, capital, and land), the returns to which compose business and household income (U.S. EPA, 2010a). The social cost of the regulation is estimated in CGE

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[4] Pre-existing distortions stem from taxes or regulations that are already in place. These create a wedge between where a market would naturally equilibrate absent intervention and where it actually equilibrates in the presence of these interventions. The literature refers to this wedge as deadweight loss because it reduces the production possibilities of the entire economy (Pizer and Kopp, 2005).

models as the change in economic welfare in the post-regulation, simulated equilibrium compared to the pre-regulation, "baseline" equilibrium. Table 2 compares key attributes of a typical CGE model to those of other model types used by the EPA to estimate costs.

Table 2. Key Attributes by Model Type

	Sector Models		Economy Wide Models
Attributes	Engineering Approach	Partial Equilibrium	CGE
Significant industry detail; rich set of technologies	√	Sometimes	
Account for facility or market constraints	Sometimes	√	√
Model changes in regulated producer behavior (e.g., input and process changes)	Sometimes	√	√
Represent interactions between multiple sectors		Limited or none	√
Model demand side response		Limited	√
Relatively easy to use and interpret results	√	√	
Relatively easy to modify for analysis of different regulations in the sector	Sometimes		√

Source: U.S. EPA (2010a)

Note that absent a credible way to represent environmental externalities in a CGE model - or the benefits that accrue to society from mitigating them – a CGE model's economic welfare measure is incomplete. The possibility of incorporating benefits into a CGE framework is discussed in the benefits white paper.

CGE models are commonly built around standard set of assumptions, although many can be relaxed to incorporate alternative specifications. Firms in CGE models are generally assumed to be profit maximizers with constant returns to scale in production. Households maximize utility from the consumption of goods and services using a specific functional form. Markets are perfectly competitive, with labor and capital fully mobile between sectors. The modeling of international trade follows the Armington assumption with goods differentiated by country of origin to allow for two-way trade for goods in the same sector. Labor is assumed to be fully employed, with no involuntary unemployment. CGE models are generally more appropriate for analyzing medium- or long-term effects of regulations since they characterize the new equilibrium (i.e., when supply once again equals demand in all markets). The time required to move from one equilibrium to another after a policy shock is not defined in a meaningful way (i.e., it is usually an instantaneous adjustment), so CGE models are generally not suited for analyzing transition costs as the economy moves to the new equilibrium. However, the EPA's Economic Guidelines acknowledge that if a transition path can be appropriately specified it is possible that one could use a CGE model for this purpose (See section 5.6 for a discussion of transition costs).

3. Representing an Air Regulation in a CGE Model

Recent years have seen extensive use of CGE models in academic analyses of policies to mitigate climate change. In contrast, since the pioneering work of Hazilla and Kopp (1990) and Jorgenson and Wilcoxen (1990), there has been relatively little academic work using CGE models for analyses of non-greenhouse gas (GHG) air regulations. Exceptions include Nestor and Pasurka (1995a, 1995b) and Dellink (2004, 2005). One reason for this focus is that the policies to mitigate climate change are likely to have much larger impacts on the economy than regulations on other types of air pollutants.

Furthermore, market-based policies commonly favored by economists, such as carbon taxes and cap-and-trade systems, are relatively straightforward to analyze with CGE models. Most CGE models include a range of taxes and other distortions. As emissions of CO_2 from fossil fuels are generally closely linked to fuel use, a carbon tax can be directly tied to fuel use in the model. Allowance prices in a cap-and-trade system are analogous to carbon taxes. A large literature, much of it developed using CGE models, examines how carbon taxes or allowance prices interact with pre-existing taxes, particularly on labor (Bovenberg and de Mooij, 1994; Parry, 1995; Bovenberg and Goulder, 1996).

Although some countries use taxes to control non-GHG air pollutants, they are rare in the United States. Instead, many U.S. air regulations take the form of an emissions rate standard or specify the use of particular types of pollution control equipment and/or the alteration of a productive process. Most CGE models also do not include non-GHG air pollutants such as sulfur dioxide, nitrogen oxides, particulate matter, or air toxics. While some abatement options are likely similar to the case of CO_2 (e.g. modifying input use to reduce emissions), others may be ruled out by the nature of the regulation (e.g., reducing output does not aid facilities in meeting an emission rate standard). In addition, end-of-pipe technologies are available for many non-GHG air pollutants, which, when used, change the nature of the relationship between emissions and fuel combustion (i.e., gross emissions are often tied directly to fuel use similar to the case of CO_2; an end-of pipe technology disrupts this relationship). See section 7 on the linking of CGE and detailed sector models to reflect the costs of CO_2 abatement technologies.

In a CGE analysis, the imposition of a regulation is frequently modeled as a "productivity shock," in which complying with the regulation takes the form of a need for additional inputs (capital, labor, intermediate goods) on top of those used to produce the good or service of the sector being regulated (Pizer and Kopp, 2005; Pizer et al., 2006).[5] This normally results in an upward movement of the sectoral supply curve. Unlike in the case of a carbon tax or cap-and-trade system, there are no revenues generated to offset

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[5] Somewhat comparable to the challenge of representing an air regulation that does not operate through price is the modeling non-tariff barriers (NTB). Fugazza and Maur (2008) note that NTBs "are not straightforwardly quantifiable and not necessarily easy to model," and that "the modeling of NTBs using general equilibrium modeling techniques is still in its early stages." Much empirical analysis is context specific (i.e., analyzing a specific instrument in a particular sector in a single country) due to the wide variety of NTBs. One approach to including NTBs in a CGE model is to rely on available econometrically estimated ad valorem equivalents to represent the wedges between the domestic and international prices of protected goods (e.g., Andrianmananjara et al., 2004).

other taxes. As discussed in section 4.3, how pollution control costs are allocated across inputs can have a significant effect on sectoral output, labor supply and other macroeconomic variables in the model.

In this section, we briefly describe the range and complexity of EPA non-GHG air regulations and then discuss the main challenges that may be encountered when attempting to represent them in a CGE model. For example, are certain representations simpler/more difficult to represent in a CGE model (e.g., there is more/less information available related to certain aspects of compliance costs or the affected universe, information maps more/less cleanly to the production function/particular industry sectors)? We anticipate that there are instances where detailed information on who is affected and how they comply may not map well or in clear cut ways to a more aggregate representation in a CGE model. Note that a number of key decision points with regard to how to represent an air regulation in a CGE model, for instance, how to enter compliance costs (e.g. through capital or labor, in a Hicks neutral way),[6] and how to characterize uncertainty, are discussed in later sections of this white paper.

While a single modeling approach may be sufficient for estimating social cost in some cases, the EPA often uses more than one modeling framework to leverage the different information that each may provide. For instance, the EPA may rely on detailed engineering analysis to identify direct compliance costs associated with the use of particular technologies. These compliance costs may then serve as a starting point for a partial or general equilibrium modeling exercise. However, care needs to be taken when using estimates from multiple sources, particularly partial equilibrium approaches that go beyond direct compliance cost estimation, as adding together social cost estimates from multiple modeling approaches can lead to double counting. See section 7 for a more in-depth discussion of the challenges encountered when linking outputs from detailed sector models with CGE models to estimate social cost.

3.1 Overview of Air Regulations

Before evaluating the challenges of representing an air regulation in a CGE model, we describe the main ways EPA air regulations vary within four very broad categories, providing several specific examples in accompanying tables. The four categories are: single sector emission rate limits; regional or state-implemented emission targets; multi-sector boiler or engine-level emission limits; and federal product standards. We organize the regulations this way as a heuristic device as there are likely other valuable ways to categorize air regulations for purposes of discussion. In addition, there may be regulations that do not fit neatly into any of these categories and, in fact, it is possible that we have missed some types of rules entirely. Still, we feel that this typology adequately captures a sufficient number of recent EPA air regulations to give the reader a sense of the regulatory landscape in which the EPA operates.

For each of the four categories of air regulations, we characterize several key attributes that may be important to consider when evaluating the relative merits of various modeling approaches:

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[6] When a change in a firm's production technology is represented in a Hicks neutral way this means that the amount of output a firm can produce for a given level of inputs changes (i.e., overall productivity either increases or declines) but the relative proportion of the specific inputs utilized (e.g., capital, labor) remains the same.

- Form of the standard: Is the regulation an emission rate or technology standard? Are limits applied at the sub-facility or facility level? Is trading/crediting allowed within or across firms? Is the rule vintage-based or differentiated along other attributes (e.g., plants, units, location)?

- Methods of compliance: Are the compliance methods available to regulated entities known? Is it expected that these methods of compliance will vary across units, firms, sectors, locations, etc.?

- Regulated sources: Is the regulated universe readily identified? In which sector(s) are the directly affected sources? How easy is it to map regulated sources to sectors?

- Unit compliance cost estimates: Are estimates of unit compliance costs available? Is the decomposition of compliance costs by input (e.g., capital, labor, intermediate inputs) available? Are some components of costs more uncertain or not available?

- Aggregate Compliance Cost: What is the expected magnitude of aggregate compliance cost? How does it compare to the size of the regulated sector?

- Implementation: Is implementation defined directly in the regulation or are key aspects left to the states or other government entities?

- Timeframe for compliance: What is the time period over which compliance occurs? What is assumed about technological innovation?

CATEGORY #1: Single Sector Emission Rate Limits

This category of regulations can be characterized as rate-based emission limits applied to an individual production unit or facility within a single sector (for example, refineries or other aspects of the oil and gas sector, cement, aluminum, iron and steel, pulp and paper, chemical production, and transportation). Regulated sectors in this category often provide key inputs to other upstream economic sectors. The regulations are typically national in scope, though a sector may be geographically concentrated in a particular region of the country. They are performance-based standards that do not require specific control measures. The regulations vary widely with regard to magnitude of costs and benefits.

The cost estimates generated by the EPA for this category of regulations are based on the expected method the facilities will use to comply. However facilities may choose alternative compliance approaches that also meet the performance standard, including changing the production process (e.g. preventing emissions by reengineering a product instead of installing control technology to capture emissions after the fact). In some cases, the standards may be vintage based (i.e., apply only to new sources). Some rules also affect private costs due to changes in fuel consumption. Rules in this category often have a relatively shorter timeframe to achieve compliance (five years or less). Examples of regulations that fall into this category are presented in Table 3 along with a description of key attributes.

Table 3: Examples of Single Sector Emission Rate Limits

ATTRIBUTE	AUTOMOBILE AND LIGHT DUTY TRUCK SURFACE COATING NESHAP (U.S. EPA, 2004)[7]	NESHAP AND NSPS: PORTLAND CEMENT MACT (U.S. EPA, 2010c)	MERCURY AND AIR TOXICS STANDARDS (U.S. EPA, 2011b)
FORM OF STANDARD	Air toxic performance standards for existing and new facilities generating emissions during the automobile coating process	Separate air toxics performance standards for new and existing cement kilns	National sub-facility emissions rate or output standards for 25MW+ power plants; vary by pollutant, plant vintage, fuel type (e.g., virgin vs. non-virgin coal, oil), technology, location; work practice standards for some pollutants
METHODS OF COMPLIANCE	Flexibility in method of compliance; expect addition of control technology (e.g., oxidizer, exhaust controls) and/or modification of coating material	Flexibility in method of compliance; mainly expect installation and operation of control technology (e.g., scrubber, activated carbon injection)	Flexibility in method of compliance (install control technology; switch fuels; shut down units that can no longer profitably produce electricity)
REGULATED ENTITIES	Good information on number, type, and location of automobile manufacturers	Good information on number, type, and location of cement kilns; project new kilns	Can identify 1,400 existing coal and oil-fired EGUs; co-generating units well known and few in number, but identifying which are subject to rule is difficult (may reduce electricity for sale to no longer be subject to rule)
UNIT COMPLIANCE COSTS	Capital costs; operation and maintenance costs; R&D for process change not quantified	Capital costs; operation and monitoring costs	Capital costs; operation and monitoring costs; fuel costs due to shifts in fuel mix; reporting and record-keeping costs; labor costs for work practices
AGGREGATE COMPLIANCE COST	$154 million (1999$)	Annualized cost in 2013 of $466 million (2005$)	Annual cost in 2016 of $9.6B (2007$)
IMPLEMENTATION	Federally implemented	Federally implemented	Federally implemented
TIMEFRAME FOR COMPLIANCE	Allow 3 years for existing sources; states may offer additional year	Allow 3 years for existing sources; states may offer additional year	Allow 3 years for existing sources; states may offer additional year

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[7] Note that for Tables 3 – 6, the date in parentheses indicates the year the regulatory analysis was conducted, not necessarily the year the regulation was finalized.

CATEGORY #2: Regional or State-Implemented Emission Targets

Regulations in this category are typically set to meet regional or state-defined targets for emission levels or air-quality standards. They often cover multiple sectors, implemented over an extended period of time (5-10 years), are typically (though not always) large in magnitude in terms of benefits and compliance costs, and may be national or regionally focused. These types of regulations often allow for flexibility at both at the firm and jurisdictional level in terms of what controls or approaches are used to achieve the emission levels or air quality standards. For example, National Ambient Air Quality Standards (NAAQS) are implemented by the states and transport regulations (i.e., when pollutants travel long distances and potentially cross state borders) may include emissions trading. Examples of regulations that fall into this category are presented in Table 4 along with a description of key attributes.

Table 4: Examples of Regional or State-Implemented Emission Targets

ATTRIBUTE	PRIMARY LEAD NAAQS (2008a)	PRIMARY OZONE NAAQS (2008b)	CROSS-STATE AIR POLLUTION RULE (CSAPR) (2011c)
FORM OF STANDARD	Implemented by states; differentiated local emission targets; potentially applies to any point or area source of lead emissions	Implemented by states; differentiated local and regional emission targets; potentially applies to any point or area source of emissions that form ozone	Sets annual/seasonal emission budgets for power plants in certain states (primarily in Eastern U.S.) for two pollutants; trading
METHODS OF COMPLIANCE	Depend on state implementation; show how target may be met based on existing technologies.	Depend on state implementation; show how target may be met based on existing technologies.	Flexibility in compliance method: States can participate in EPA interstate cap and trade or meet individual state emissions budget
REGULATED ENTITIES	Expected to affect a wide array of sectors but which entities and in which sectors is uncertain	Expected to affect a wide array of sectors but which entities and in which sectors is uncertain	Regulates emissions from 25 MW+ power plants in covered states
UNIT COMPLIANCE COSTS	For illustrative control strategy; when all identified controls are applied but region still not in compliance, use extrapolated cost for unidentified technologies	For illustrative control strategy; when all identified controls are applied but region still not in compliance, use extrapolated cost for unidentified technologies	Incremental capital costs, and fixed and variable operating costs including fuel switching
AGGREGATE COMPLIANCE COST	$0.15B to 3.2B in 2016 (2006$)	$7.6B to 8.8B in 2020 (2006$)	$0.8 B (2007$) in 2014
IMPLEMENTATION	Implemented by states	Implemented by states	Federally implemented, but states have option to implement
TIMEFRAME FOR COMPLIANCE	8 years	10+ years	Phase 1 starting in 2012, Phase 2starting in 2014.

CATEGORY #3: Multi-Sector Boiler or Engine-Level Emission Rate Limits

These regulations are usually federally set rate-based emission limits but are applied to a disparate set of boilers or engines used across multiple sectors. These regulations are typically national in scope and have large aggregate compliance costs due to the large number of units to which the emission rate limits apply. The compliance time is typically five years or less from promulgation. Examples of regulations that fall into this category are presented in Table 5 along with a description of key attributes.

Table 5: Examples of Multi-Sector Boiler or Engine-Level Emission Rate Limits

ATTRIBUTE	NATIONAL EMISSION STANDARDS FOR BOILERS (MAJOR SOURCES)[8] (2011d)	NATIONAL EMISSION STANDARDS FOR STATIONARY INTERNAL COMBUSTION ENGINES (2013b)
FORM OF STANDARD	Separate air toxics standards for new and existing industrial, commercial, and institutional boilers and process heaters	National emission standards for hazardous air pollutants for existing stationary spark-ignition (SI) reciprocating internal combustion engines (RICE)
METHODS OF COMPLIANCE	Flexibility in compliance method; expect mostly installation and operation of capital equipment (e.g., fabric filters, electrostatic precipitators, wet scrubbers, tune-ups, combustion controls, etc.)	Flexibility in compliance method; expect mostly installation and operation of add-on equipment (e.g., oxidation catalysts or selective catalytic reduction)
REGULATED ENTITIES	Multiple sectors; total number and types of boilers known but location/specific sectors of boilers and process heaters difficult to estimate	Multiple sectors; internal combustion engines generate electric power, pump gas or other fluids, or compressed air for machinery
UNIT COMPLIANCE COSTS	Installation and annual costs of capital equipment; monitoring and testing costs	Installation and annual costs of capital equipment; monitoring costs
AGGREGATE COMPLIANCE COST	Annualized cost in 2016 of $1.4B to $1.6B (2008$)	Annualized cost in 2013 of $115 million (2010$)
IMPLEMENTATION	Federally implemented	Federally implemented
TIMEFRAME FOR COMPLIANCE	Allow 3 years for existing; states may offer additional year	Allow 3 years for existing sources; states may offer additional year

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[8] Separate new source performance standards for industrial, commercial, and institutional boilers and process heaters that operate as solid waste incinerators were promulgated in 2011, covering multiple sectors and allowing flexibility in compliance. The exact number and location of incinerators is difficult to estimate. If an incinerator stops combusting hazardous waste it may be covered under the boiler rule.

CATEGORY #4: Federal Product Standards

This category includes federal standards that regulate features of manufactured products used by households and other sectors. Examples include in-use emission rate requirements for vehicles and product content requirements for fuels, coatings, or consumer products. Product bans have similar effects in that the composition of products available in the market is constrained. What is in common among regulations in this category is that they focus on certain product qualities and/or availability instead of on emissions that stem from the product manufacturing process.[9] While there are many products potentially affected, regulations typically apply to the product manufacturer. Some regulations may allow for manufacturer-based averaging or trading across manufacturers. Examples of regulations in this category are presented in Table 6 along with a description of key attributes.

Table 6: Examples of Federal Product Standards

ATTRIBUTE	EMISSION STANDARDS FOR NEW NONROAD VEHICLE ENGINES (2002)	VOLATILE ORGANIC COMPOUND (VOC) EMISSION STANDARDS FOR CONSUMER PRODUCTS (1996)
FORM OF STANDARD	Separate emission rate-based standards for new vehicles or engines, differentiated by pollutant, use/type, and engine size (e.g., snowmobiles, off-highway motorcycles, ATVs; large industrial spark-ignition engines)	Separate VOC content limits for 43 consumer product categories used as cleaning products (e.g., air fresheners, wood floor wax), personal care products (e.g., hair mousse, nail polish remover), and insecticides.
METHODS OF COMPLIANCE	Flexibility in compliance method; expect manufacturers to modify engine technology, change from two- to four-stroke engine, or improve diesel combustion and after-cooling	Limits met through product reformulation; includes potential exemption if can show emissions less than or equal to representative complying product in same category
REGULATED ENTITIES	Engine manufacturers across a variety of transportation subsectors	Approximately 220 manufacturers, distributors, or importers
UNIT COMPLIANCE COSTS	Fixed R&D costs; variable costs to build/certify new products; savings from better engine performance and reduced fuel consumption; may negatively impact some attributes (e.g., power to weight ratio, reliability)	There are virtually no capital costs, except for development of new, reformulated products. Variable costs include recordkeeping and reporting
AGGREGATE COMPLIANCE COST	Cost to comply is $1.9B; $4.3B in fuel savings (~2001$)	Annualized cost of $27 million (1995$); prices of consumer products expected to increase by less than one percent
IMPLEMENTATION	Federally implemented	Federally implemented
TIMEFRAME FOR COMPLIANCE	2-4 years after promulgation; longer phase in for some standards	Less than 1 year from promulgation

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[9] It is worth noting that process change may also be an effective method of compliance for other categories of regulations even though that is not the focus of the regulatory requirements.

3.2 Challenges in Representing an Air Regulation in a CGE Model

This section briefly discusses several challenges that may be encountered when attempting to represent an air regulation in a CGE model. We select one example from each table in the previous section to facilitate a better understanding of some of the specific types of issues encountered by an analyst when attempting to use a CGE model to estimate social costs for these four categories of regulations.

Single Sector Emission Rate Limits - MATS Example (Category #1)

Typically the EPA has relatively good information on which entities will be affected, the technologies available for compliance, and engineering-based cost estimates associated with these technologies. However, there are several challenges related to estimating the social cost of a regulation such as the MATS example from Table 3 in a CGE model.

Methods and costs of compliance likely vary significantly by type of generating unit, though generally it is assumed that utilities comply by using the least cost strategy available. For MATS, the compliance strategy chosen is expected to depend on factors such as (but not limited to) facility age, the technology used by the facility, forecasted prices of different types of fuel and the different grades of fuel available, the costs of retrofitting technology for a specific facility, the costs of building new facilities or new capacity at other facilities, and shut-down costs. Geographical location is also important due to fuel availability, degree of competitiveness in markets for electricity, and electricity transmission constraints between regions.[10] There are also important and complex relationships in the control of air pollutants. For example, one coal type may contain more of one pollutant and less of another relative to another coal type. Also, certain pollution controls that target one pollutant may influence the level of another.

While CGE models of the U.S. economy vary greatly in sector detail, even those that are relatively disaggregated (e.g., some versions of USAGE have 500 sectors) often represent electric utilities as a single category. CGE models that have been used to evaluate the implications of carbon policies sometimes further disaggregate industries based on the production and generation of energy. For instance, the Economic Model for Environmental Policy Analysis-Computable General Equilibrium (EMPAX-CGE) and the Intertemporal General Equilibrium Model (IGEM) both distinguish gas from electric utilities as well as coal, oil, and natural gas extraction. However, relative to the specifics of a regulation such as MATS, they are still relatively aggregate: These models do not allow an analyst to capture differences in compliance options associated with multiple emission limits differentiated by vintage, fuel source, and technology, the complementarities and tradeoffs in control of these pollutants, or the flexibility afforded regulated entities in methods of compliance. Nor do they allow for separating out electric generating units not affected by the regulation.

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[10] The installation and operating costs of pollution control technologies are engineering estimates and generally well-known, though some uncertainty exists regarding the cost of emerging abatement technologies. For example, the electricity sector has had relatively limited but meaningful experience with dry sorbent injection, which can be used to control hydrochloric acid. The cost of new generating capacity or of increased operation of existing units to replace generating units that are shut down is also relatively well known. Likewise, there may be differences in the fuel extraction process across locations that may not be captured by a CGE model. For example, coal production is more capital intensive in in the western U.S. than in the east.

Note that a detailed partial equilibrium sector model may be able to model many of the methods individual sources use to comply with MATS that cannot be adequately represented in a CGE model, as well as consequent effects on electricity and natural gas prices. This type of sector-specific model does not capture general equilibrium impacts through the rest of the economy, and how those changes in turn affect prices faced by the electricity sector, as a CGE model would. However, applying certain assumptions it is possible to link the results from a sector-specific model to a CGE model. We discuss the potential for and challenges of linking these two types of models in Section 7 of this paper.

Regional or State-Implemented Emission Targets - Ozone NAAQS Example (Category #2)

Estimating the social cost of a region or state-implemented federal standard is challenging regardless of modeling strategy. For example, implementation of a NAAQS regulation can take a decade. Once the regulation is promulgated, states must design control strategies, submit them to the EPA for approval, and then implement them. In the case of the ozone NAAQS example in Table 4, the final regulation was promulgated in 2008 with an expectation that it would be fully implemented by 2020. This makes it harder to confidently characterize the baseline absent the policy (e.g., predictions of emission source growth and other air quality regulations that may be promulgated during the implementation time horizon).

Other challenges include uncertainty regarding what sectors or sources may be affected by the rule, how sources will choose to comply with the regulation, and the future availability of emission control technologies. The NAAQS standards do not specify which emission sources and technologies must be used to meet the federal emissions limit.[11] Instead, states and counties choose the combination of emission reduction measures across a wide variety of sectors to achieve the standard. The availability of control technologies is of particular importance given that the benefits and costs of a regulation are often evaluated under the assumption of 100 percent compliance. Once all identified control technologies have been applied, some areas of the country may still be modeled as out of compliance (i.e., out of attainment) with the emissions limit. In these cases, the EPA has the challenge of extrapolating compliance costs for a set of unidentified controls to bring these remaining areas into compliance with the standard.

The EPA typically identifies the least cost approach available for meeting the standard using identified control strategies. However, it considers this only illustrative as strategies will likely vary by state or region to reflect location specific mixes of emission sources, meteorological condition, and preferences for different compliance approaches (e.g., they may opt for a market-based trading approach, specify abatement technology or fuel switching strategies for new sources, invest in public transportation or other lower emission commuting options, and/or conduct vehicle retrofits for existing mobile sources). Even when engineering and partial equilibrium compliance cost estimates account for regional differences in emission sources, CGE models often do not have enough spatial resolution and may not reflect the same regional configuration to map them directly.

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[11] National Ambient Air Quality Standards (NAAQS) for criteria pollutants (carbon monoxide, lead, nitrogen dioxide, ozone, particle pollution, and sulfur dioxide) set a maximum atmospheric concentration level of pollution that is not to be exceeded. This level can be measured over a short period of time, such as an 8 hour average ozone level, an annual level, or a combination of standards for short and long average time periods, such as the annual and 24 hour standards for particulate matter concentrations.

As in the case of the MATS example, CGE models are typically too aggregate to capture variation in methods of compliance (for instance, compliance options that vary across new versus existing sources within a sector, apply to a narrow sub-sector, or reduce area sources that are not sector-specific). Extrapolated costs in areas where identified, available technologies are not sufficient to meet the NAAQS are particularly challenging in a CGE context because they lack specificity about the types of inputs required to comply and are not apportioned to specific industries. This leaves the analyst with a choice between omitting these costs from the economy-wide estimation, which renders an estimate of social cost incomplete, or making additional assumptions about how and in what industries they will be implemented, further exacerbating estimation uncertainty.

Multi-Sector Boiler or Engine-Level Emission Rate Limits - Boiler MACT Example (Category #3)

Because these types of regulations are applied to emissions from the operation of a boiler or engine, the regulated universe is often highly disparate and difficult to identify. While there is typically good information on the compliance technology options available and the costs associated with implementing them, the distribution of these costs across sectors and regions is uncertain. As with the MATS and Ozone NAAQS examples, CGE models do not provide enough detail to allow for an accurate depiction of how technology choice varies by boiler type for the Boiler MACT example from Table 5. In many cases this variation occurs at a sub-sector level and likely varies between existing and new boilers given different standards. However, while some CGE models represent manufacturing as a single or relatively small number of sectors it is not uncommon for CGE models to separately model the four main manufacturing sectors affected (food products, chemical, wood product, and paper). Representing commercial and institutional boilers may be more complicated. For example, hospitals and universities are likely categorized in the service sector, and while some CGE models may differentiate between education and health care services these sectors encompass many other types of establishments (i.e., education services also include elementary middle and high schools and training centers, while health services include nursing care and residential care facilities).

Linking to a detailed partial equilibrium sector model to capture heterogeneity in compliance may be more complicated compared to MATS, due to the wide range of sectors affected for which detailed models may be unavailable (and even if available, linking to multiple sector models is likely even more complicated than linking to a single model). In this sense, the boiler MACT has more in common with the Ozone NAAQS. In addition, there is not necessarily a linear relationship between hazardous air pollutant (HAP) emissions and fuel use, which is often used to make assumptions about the way abatement costs enter the production function.

Federal Product Standards - VOC Emissions Standard for Consumer Products Example (Category #4)

The cost of a product standard such as the VOC Emissions Standard for Consumer Products example from Table 6 may be difficult to estimate because it involves research and development to reformulate products. Likewise, regulatory requirements may affect the quality and availability of certain consumer products, which are also often difficult to estimate ex-ante. In some cases, attributes valued by the consumer could be negatively affected (e.g, effectiveness, reliability, and power); standards may also

result in improved products (e.g., new paint colors, better durability, and enhanced performance). In the case of the VOC Emissions Standard for Consumer Products, process changes also likely vary by product.

Process changes may not necessarily require new capital equipment or additional labor to produce; a firm may only need to invest in research and development in the initial years to reformulate a product while costs in subsequent years are small. When the product seems nearly identical to its pre-regulation version from the consumer's perspective, representing compliance costs in a CGE model's production function may be more straight-forward than in the previous regulatory examples. This type of process change seems close in spirit to a Hicks neutral change in technology that leaves the proportion of other inputs in production unchanged. However, if VOC content requirements result in an entirely new product or a change in product attributes that affect its customer appeal, the use of the Hicks' neutral approach would miss market responses that affect social cost.

The VOC Emissions Standard mandates a change in the way a myriad of products are manufactured to reduce VOC content. Many of the consumer products affected by the regulation are narrowly defined and likely only represent a small portion of much more aggregate sectors in a CGE model. As such, substitution away from a regulated product to unregulated alternatives within the same sector (since they do not face the costs to comply they are now relatively cheaper) would be entirely missed by a CGE model. As with the boiler MACT example, linking a CGE model to a detailed sector model to better capture heterogeneity in compliance strategies and their accompanying costs would require considerable information given the large number of disparate products covered by the regulation. In addition to capturing changes in the price of these products it may also be important to reflect changes in product quality when evaluating social cost. However, sector outputs are usually assumed to be homogenous in a CGE model.

4. Sensitivity of Social Cost to Regulation Attributes

Identifying the most appropriate modeling tools for analyzing social cost depends on the regulation's details, as highlighted in the previous two sections of the paper; data requirements; model availability; and constraints on time and budget. The EPA's Economic Guidelines also identify several technical factors to consider in model selection, including: "the types of costs being investigated, the geographic and sectoral scope of the likely impacts, and the expected magnitude of the impacts" (U.S. EPA 2010a).

Since air regulations are complex and vary widely (e.g., magnitude of compliance costs, sectors being regulated, what effects can be quantified), it is likely that the modeling tools deemed most appropriate for cost estimation will be regulation-specific. For some regulations, an engineering or partial equilibrium approach may be adequate to capture the expected social cost. For other regulations, compliance costs or partial equilibrium welfare measures may be inadequate measures of overall social cost. In these cases, a general equilibrium approach may add value over an engineering or partial equilibrium approach.

This section considers the sensitivity of social cost estimation in a CGE framework to a number of issues associated with regulatory attributes as highlighted in Section 3. In particular, each factor is discussed with regard to how it may affect the technical merits of using a CGE model for estimating the social cost of a regulation. The intention of this section is not to review/critique past modeling approaches used by the

EPA or outside groups but rather to set the stage for a broader discussion of these issues as laid out in the charge. The specific factors are:

- Magnitude of expected compliance costs.

- Time horizon for implementation.

- How compliance costs are entered into a CGE model,

- Number and types of sector(s) directly and/or indirectly affected, and magnitude of potential market effects, and

- Degree of expected technological change

Discussion of the sensitivity of social cost to these factors has been gathered from the existing literature, though few papers look specifically at the effects of regulation; the EPA's experience using CGE models to analyze regulations; and results from a limited set of illustrative runs using the static version of the EMPAX-CGE model, also referred to as EMPAX-S.

4.1 Magnitude of Compliance Costs

CGE models are recognized as being "best suited for estimating the cost of policies that have large economy-wide impacts, especially when indirect and interaction effects are expected to be significant" (U.S. EPA, 2010a). For instance, the EPA's study of the prospective effects of the Clean Air Act Amendments from 1990 to 2020 (U.S. EPA, 2011a) found that there are substantial secondary effects of compliance costs on the overall economy, a large portion of which likely result from energy price increases and the diversion of capital from activities that enhance long-term productivity to investment in pollution control equipment in the industrial sector. The EPA's Economic Guidelines also recognizes that CGE models "are generally not well suited for estimating the effects of policies that will affect only small sectors or will impact a limited geographic area" (U.S. EPA, 2010a). However, what constitutes a large (versus a smaller sector/region specific) impact that may merit use of a CGE (versus a partial equilibrium) approach is not well defined in the literature.

The EPA's air regulations range widely with regard to magnitude of aggregate compliance costs. We distinguish between four compliance cost bins based on the estimated annual costs of air regulations promulgated between 2003 and 2013 (as reported in OMB 2014 (in 2001$)):

• $100 million – this is the threshold at which Executive Order 12866 requires BCA,

• $0.5 billion – many air regulations had compliance costs near this amount during the time period

• $3 billion – many air regulations had compliance costs in the $1 - $3 billion range during the time period

• $10 billion – no air regulation had higher compliance costs than $10 billion during the time period

To better understand how the magnitude of compliance cost is reflected in economy-wide social cost estimation, we used the EMPAX- S CGE model to conduct a set of simulations. For each of the 25

manufacturing sectors in the model, we entered each of the four compliance cost amounts listed above and calculated the equivalent variation (EV) – for a total of 100 simulations.[12]

Figure 2 shows the range (horizontal gray bar) and average (vertical black bar) of the EV calculated for the 25 sectors for each of the four compliance cost amounts. The range of estimates is wide and expands in both relative and absolute terms as compliance costs increase. The average tends toward the lower end of the range. In the case of the set of $10 billion compliance cost simulations, in a number of simulations EV is smaller than the compliance cost. All of these occurrences are for sectors where base year total production costs are in the $20-30 billion range. We include these sectors for illustrative purposes but to avoid the extreme values problem, we next perform simulations where compliance costs are set at a percentage of base year total production costs.

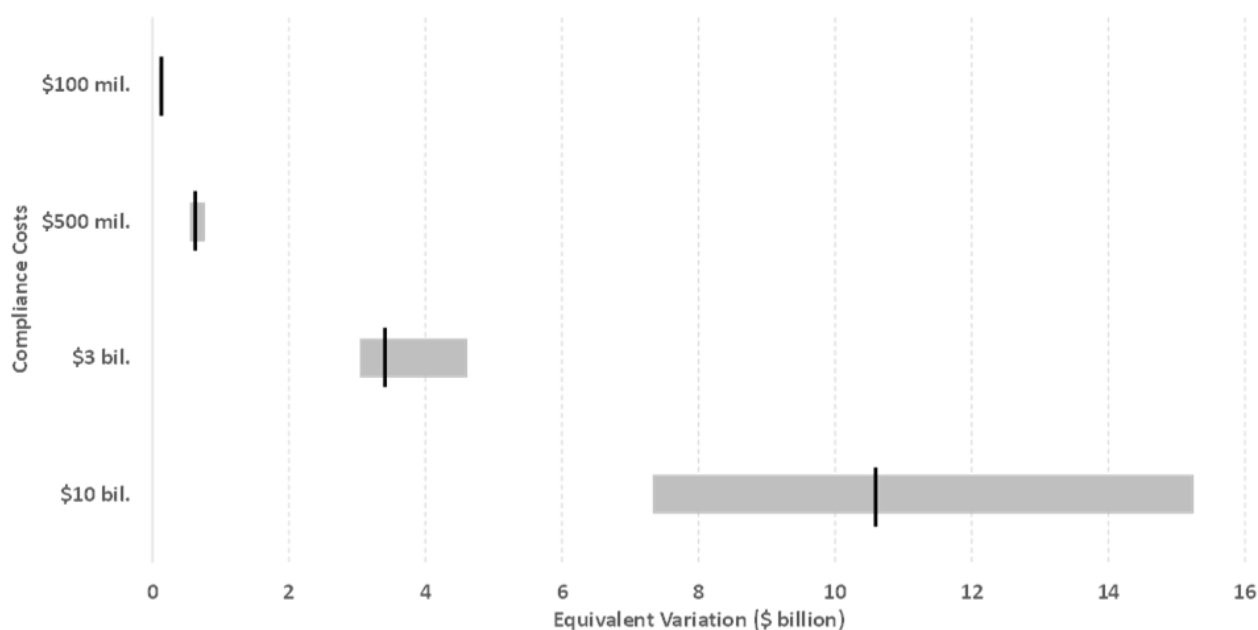**Figure2: EV: Range and average for 25 manufacturing sectors**

Figure 3 shows the range and average of the percentage difference between EV and compliance costs, where compliance costs are entered as 1, 2, 3, and 4 percent of base year production costs.[13] Although

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[12] EV is a monetary measure of the change in utility brought about by changes in prices and incomes, and focus on changes in consumer welfare rather than on changes in total final demand (U.S. EPA, 2010a). See section 6 for more discussion of this and other measures of economic welfare.

[13] The 2005 Pollution Abatement and Expenditure Survey (PACE) reports capital abatement expenditures to reduce air emissions as about 3 percent of total new capital expenditures (from the Annual Survey of Manufacturers) for all reporting industries combined. Some industries report a much larger proportion of abatement expenditures – paper manufacturing has abatement capital expenditures that are 6.8 percent of total new capital expenditures while petroleum and coal products manufacturing has abatement capital expenditures of almost 14 percent - while others report noticeably lower expenditures to reduce air emissions – the machinery manufacturing sector has abatement

the averages tend toward the lower end of the ranges, the ranges themselves are quite wide. For the 1 percent compliance cost case, the range extends from 9 percent to 54 percent. As compliance costs increase, the upper end of the range decreases slightly while the lower expands enough that the overall range is greater. The average difference between EV and compliance cost decreases slightly from 17 percent to 15 percent as compliance costs increase from 1 percent to 4 percent of base year production costs. While these simulations use a single static model only, they demonstrate that differences between partial and general equilibrium estimates of cost can vary greatly by sector and simple a priori generalizations should be avoided.

Figure 3: Percent EV differs from compliance cost: Range and average for 25 manufacturing sectors
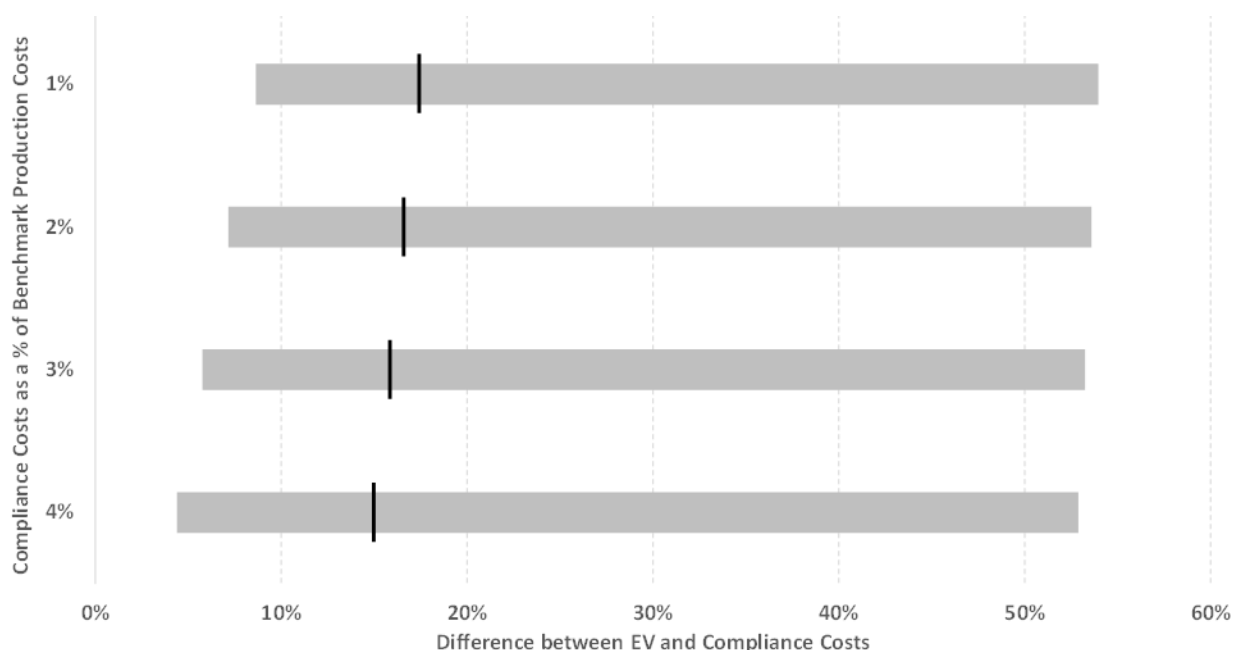
4.2 Time Horizon

Often the EPA estimates the social cost of a regulation at a given (future) point in time. Such estimates provide snapshots of the expected costs for firms, government, and households but do not allow for behavioral changes from one time period to affect responses in another time period. However, effects over time may be important when investment in capital to comply with the regulation in one period

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capital expenditures that are 0.3 percent of total new capital expenditures while fabricated metal products manufacturing has abatement capital expenditures of 1.2 percent. It is important to keep in mind, however, that capital expenditures reported to PACE are for requirements across all Federal air regulations combined, while the focus of this white paper is on how to analyze social cost associated with a single air regulation.

affects investment decisions in future periods.[14] Pizer and Kopp (2005) note that static productivity losses from environmental regulations are amplified over time due to their effect on capital accumulation (a lower capital stock over time reduces economic output and therefore welfare). A static model would miss this effect. Pizer and Kopp (2005) state that the "additional cost of this accumulation effect on welfare can be as much as 40 percent above the static cost that ignores changes in capital stock." Hazilla and Kopp (1990) and Jorgenson and Wilcoxen (1990) have also shown that this effect is potentially significant. It is important to note, however, that this conclusion is based on studies of large-scale changes in environmental regulation (i.e., Hazilla and Kopp, and Jorgenson and Wilcoxen examine the combined welfare effects of the 1972 Clean Water and 1977 Clean Air Acts).

In addition to capital-induced growth effects, the evaluation of social cost in a dynamic framework may be important when a regulation is expected to affect product quality, productivity, innovation, and changes in markets indirectly affected by the regulation in a way that impacts consumer and producer surplus over time (U.S. EPA, 2010a).

The time interpretation of a CGE model depends on whether the model is static (one period) or dynamic (multiple periods). Static models produce a single-period representation of how the economy responds to a policy shock. Dynamic CGE models are long-run models, often calibrated to a starting year, that produce estimates for a set of future years relative to a projected baseline. The EPA's Economic Guidelines advises that if the intertemporal effects of a regulation on non-regulated sectors are expected to be significant, a dynamic CGE model may yield useful insights. That said, the evolution of variables in the model sometimes depends on exogenously imposed assumptions. For instance, modelers sometimes need to constrain the pace at which some variables in the model change (e.g., how quickly technology changes) based on an external assessment of what is technically feasible. Static and dynamic models are discussed in more detail in section 5.2. The representation of technological change is discussed in sections 4.4 and 5.6 of this paper.

Regulatory Representation and Timing

Another important time-related issue is how far out into the future a CGE model produces estimates. The EPA's Economic Guidelines states that, "generally, the duration of important effects of a policy determines the period chosen for the analysis and baseline." Since a static CGE model can only produce a snapshot of the social cost of a regulation for a given year (e.g., 2020) it may or may not be representative of the policy's effects. Even when an analyst determines that it is important to estimate the social cost of regulation over a longer period of time, a dynamic CGE model may stop short of the end-year for capturing important regulatory effects, in which case social cost estimates might be biased downward. When compliance costs are not available for all future years, a forward-looking CGE model has a greater ability to smooth costs over time. However, this may mask the full economic impact of a policy. To ensure that the model does not underestimate costs when policy costs persist into the future, one may need to extrapolate costs to the end of the CGE model horizon.

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[14] "For example, if a regulation requires firms in the electric utility sector to invest in pollution control equipment, they may not invest as much in electric generation capacity as they would have in the absence of the regulation. This may result in slower growth in electricity output" (U.S. EPA 2010a).

In dynamic models, time steps between periods are chosen to provide enough detail to show the adjustment to policy over time, while using a manageable number of time periods for computational reasons. Because dynamic CGE models are often solved over periods of 50 years or more, it is not always practical to solve each individual year. A five-year time step is used in models such as the dynamic version of EMPAX-CGE (also referred to as EMPAX-D) and EPPA. In recursive models, time steps represent shocks that move the baseline economy from one period to the next. The Global Trade Analysis Project (GTAP)-Dyn model describes shocks to the time variable, t, as defining the model period, and "shocks to other exogenous variables represent accompanying changes in external circumstances" (Ianchovichina and McDougall, 2000). This implies that, when using a dynamic CGE model, the year in which a regulation comes into effect may not be explicitly modeled. Due to the expense and time requirements to adjust the baseline, adding a new solution year may not be an option. For MATS, the EPA used 2015 as a proxy for the year in which compliance with the regulation begins (i.e., 2016). Regulations that are introduced gradually or vary timing of compliance by region or state pose additional challenges for model representation.

4.3 How Compliance Costs Are Entered into the Model

We previously noted that the imposition of a regulation in a CGE model is frequently modeled as a "productivity shock," in which complying with the regulation creates a need for additional inputs in addition to those already used to produce the good or service of the regulated sector.[15] The total cost of these additional inputs may be derived from detailed estimates of compliance costs from an engineering or partial equilibrium model. This, however, begs the question of how to allocate estimated total abatement cost among inputs specified in the CGE model.

As detailed information about the composition of abatement costs and/or how to map them into inputs in a CGE model is often lacking, one frequently used approach is to allocate the abatement costs in direct proportion to the inputs – capital, labor, and intermediate goods – used in the regulated sector of the CGE model. In other words, regulatory requirements do not change the proportion of labor, capital, or other inputs in the firm's production function. This "Hicks-neutral" allocation is the approach taken by Hazilla and Kopp (1990) and Jorgenson and Wilcoxen (1990). Ballard and Medema (1993) allocate all of the abatement costs to capital and labor inputs only.

Using a CGE model of the German economy with a separately defined sector for pollution control based on detailed abatement cost data, Nestor and Pasurka (1995a, 1995b) compare the impacts of abatement costs allocated across inputs consistent with the German data with impacts simulated using Hicks-neutral and capital-labor only abatement cost allocations. They find that there are significant differences in sectoral impacts between the simulations using the German data for the cost allocation and those using the more ad hoc allocations.[16] In particular, relative to the data-driven specification, the Hicks neutral cost

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[15] For alternatives to this approach to modeling the introduction of a regulation see Aiken et al. (2008).
[16] Nestor and Pasurka, and others use surveys and other data to construct 41-sector input-output tables for the U.S. that separate out environmental protection activities (U.S. EPA, 1995b). The input-output tables are constructed for

allocation approach tends to underestimate output changes because it allocates a smaller proportion of abatement expenditures to labor and capital than occurs in reality. In contrast, the capital-labor only abatement cost allocation approach tends to overestimate output changes because it assumes abatement processes do not rely on intermediate inputs; thus, it fails to account for offsetting indirect effects.

Nestor and Pasurka (1995b) focus on sectoral impacts in their comparison of the allocation of abatement costs in CGE models instead of how the allocation of abatement costs may affect economy wide measures. To do so, as in section 4.1 where we looked at the effect of the magnitude of compliance costs on economy wide impacts, we perform a set of simulations using the EMPAX- S static CGE model. As a bounding exercise, in succession for each of the 25 manufacturing sectors in the model, we allocate $1 billion of compliance costs to (i) capital only, (ii) labor only, and (iii) intermediates only. We also allocate the $1 billion of compliance costs according to Hicks-neutral shares.[17]

Figure 4 shows the range (horizontal gray bar) and average (vertical black bar) of the EV calculated for the 25 sectors for each of the four cost allocations. The differences are quite large. For the capital-only allocation, the range of EVs calculated with the model extends from 50 percent greater than the compliance costs, to almost 100%. The average for the 25 sectors is 60 percent. For the intermediates-only allocation, on the other hand, the range goes from 2 percent *less* than the $1 billion in compliance costs to 16 percent more, with an average of 2 percent. The range for the labor-only cost allocation is narrower than for the capital-only allocation and the average is lower at 38 percent. The average for the Hicks-neutral allocation is 17 percent, lying between the factor-only and intermediate-only allocations, as the Hicks-neutral shares include both types of inputs.

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the years 1977 and 1982. In a separate paper (U.S. EPA, 1995a), they estimate vectors for inputs purchased for air, water, and solid waste environmental protection activities for 1991. Data from these studies are used to allocate inputs in CGE model simulations for the EPA's prospective study of the benefits and costs of the Clean Air Act from 1990 to 2020 (U.S. EPA, 2011a). Unfortunately, collection of some of the survey data used by Nestor and Pasurka has been discontinued and extensions of their work to more recent years have not been attempted.

[17] We chose not to allocate costs using a subset of the Nestor-Pasurka data for this exercise.

Figure 4: EV with $1 billion in compliance costs for 25 manufacturing sectors: Range and average
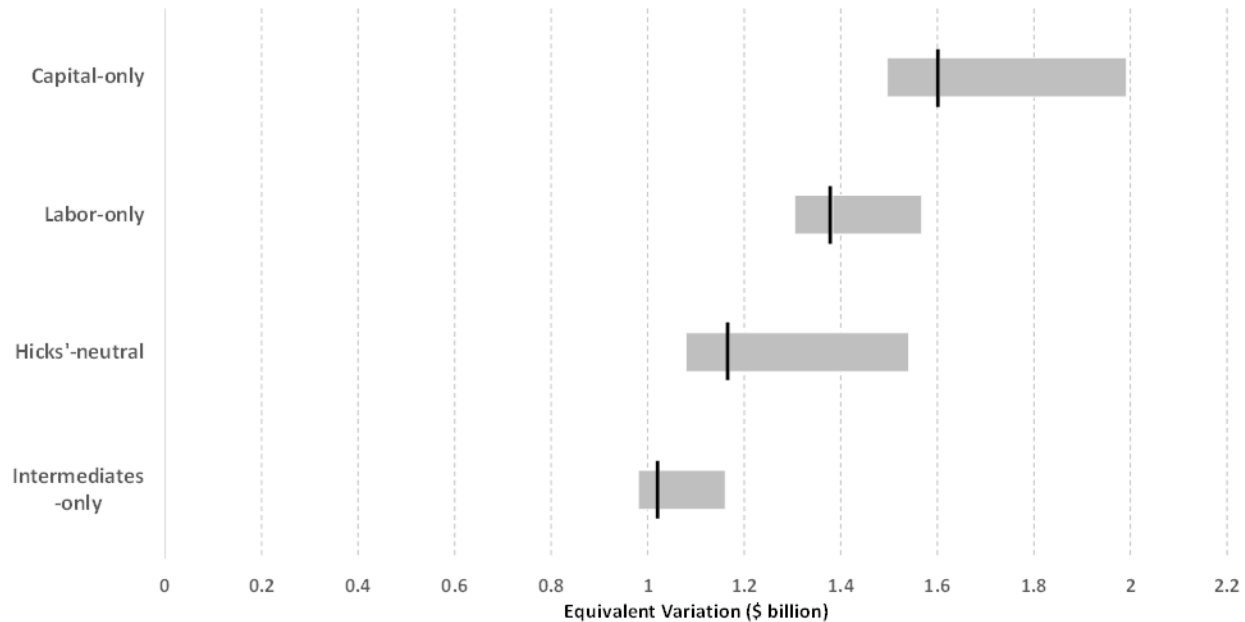
As demonstrated by Fullerton and Heutel (2010), non-revenue raising environmental regulations can have significant effects on factor prices and in turn on real incomes. In our simulations, a productivity shock, regardless of the cost allocation, lowers factor prices. Productivity shocks with capital-only and labor-only allocations have a greater combined effect on factor prices than is the case with the intermediate-only allocation as the factor-only shocks place a greater overall burden on the factors. In the EMPAX-S static CGE model, capital is able to move between sectors, but the total stock is fixed. Labor supply, however, responds to changes in both the wage rate and non-labor income (e.g. through changes in a representative agent's income from ownership of the capital stock). In our simulations of the capital-only allocation, labor supply falls, increasing the impact of the productivity shock. With all of the other allocations, however, labor supply *increases*, reducing the impact of the shock. We can see this in Figure 5, where we have run the same simulations but with a fixed labor supply. The average for the capital-only allocation is now lower, while for all of the other allocations, the average is greater. Without the impact of the change in labor supply, the averages for the capital-only and labor-only allocations are almost identical (although the range is still wider for the capital-only allocation).

Figure 5: EV with $1 billion in compliance costs for 25 manufacturing sectors: Range and average (Labor supply fixed)
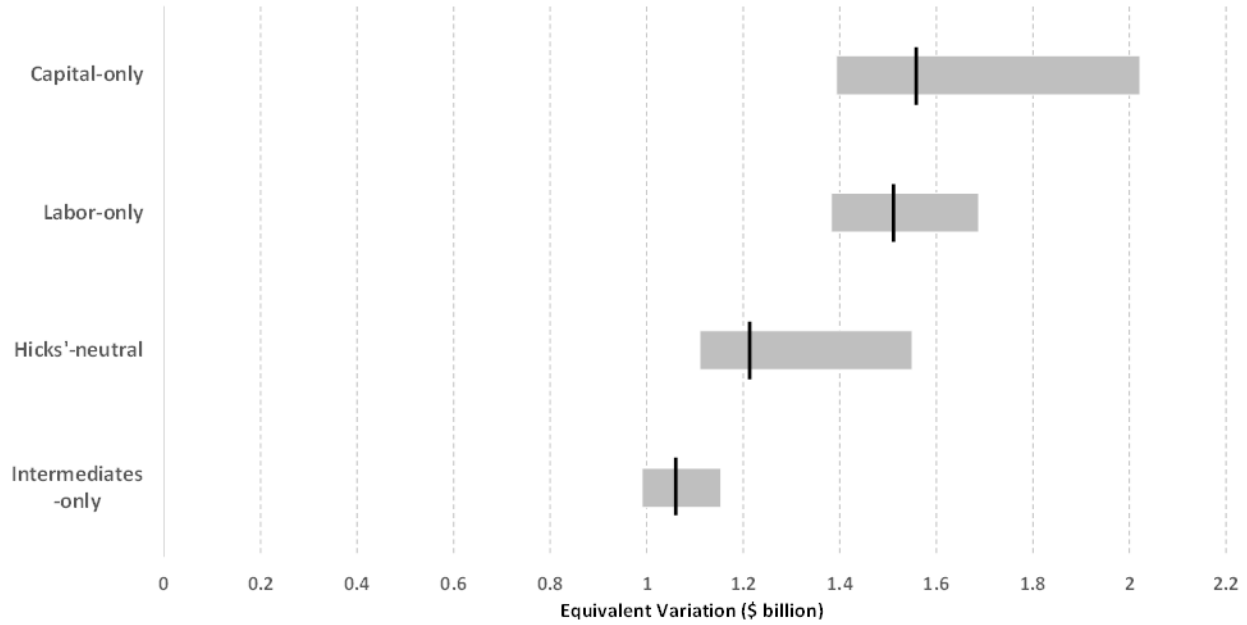
4.4 Expected Technological Change from Air Regulations

Estimating the social cost of an air quality regulation over a relatively long time horizon requires assumptions about future technological change. [18] It has long been recognized that both the stringency and approach of environmental regulation that is taken (i.e., technology standard, performance standard, or economic instrument) may influence the degree to which it induces technological change (e.g., Magat, 1978; Fischer et al., 2003).

Jaffe et al. (2002) lay out a conceptual framework for understanding how technological change in response to environmental regulation may affect the relationship between inputs and output, ultimately reducing the unit costs of production. They represent the economy's aggregate production function in logarithmic form, where y_t is the growth rate in output (Y) over time, and l_t, k_t, and e_t are the growth rates for the inputs to production, labor (L), capital (K), and an environmental input (E), respectively:

$$y_t = A_t + \beta_{Lt}l_t + \beta_{Kt}k_t + \beta_{Et}e_t .$$

Hicks neutral technological change is represented in this framework through a change in A_t ; in other words, an increase in A_t means overall productivity increases. It is possible to produce more output using the same conventional inputs (L, K, and E) as before (or conversely, to produce the same level of output from smaller quantities of inputs). There is also the potential for "biased" technological change. An

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[18] Technological change represents a change in the way in which productive activity occurs. Jaffe, et al. (2002) define technological change as a process that incorporates invention, innovation, and diffusion.

environmental regulation may affect the growth rate of one or more inputs over time or change the relative productivity of inputs to production, which is captured by a change in one or more of the βs.

Whether innovation induced by an individual regulation is more appropriately modeled as a change in A or in one or more βs is an empirical matter. Compliance with an environmental regulation may result in the adoption of existing technology, improvement of or application of existing technology to a new use, and/or development of entirely new technologies or processes (Sue Wing, 2006a). Newell et al. (1999) point to evidence of technological change that is biased toward or away from energy efficiency in appliances over time, but find that the direction of the bias is related to changes in relative energy prices instead of regulation.[19] The EPA's Economic Guidelines notes that, "despite its importance as a determinant of economic welfare, the process of technical change is not well understood. Different approaches to environmental regulation present widely differing incentives for technological innovation. As a result, the same environmental end may be achieved at significantly different costs, depending on the pace and direction of technical change."[20]

The empirical literature also has noted that variable costs of production or environmental abatement tend to decline over time with cumulative experience. While the explanations for why this occurs vary, the evidence for such "learning" is compelling enough that OMB now asks agencies to consider the potential for learning effects when analyzing the cost of regulation. For instance, the EPA has applied technology-specific learning curves to a select set of new technologies when estimating compliance costs for light duty vehicle regulations. When analyzing the prospective costs and benefits of the Clean Air Act Amendments from 1990 – 2020 (U.S. EPA 2011a), the EPA adjusted the costs of compliance (for local controls in non-attainment areas) downward by 10 percent, on average, for every doubling of emission reductions. However, when a CGE model is also used to evaluate social costs, a key question is how assumptions regarding technological innovation that are applied to engineering estimates interact with assumptions about technological innovation already integrated into a CGE model.

4.5 Number and Type of Sectors

As noted in the EPA's Economic Guidelines "[a]s the number of affected markets grows, it becomes less and less likely that partial equilibrium analysis can provide an accurate estimate of social cost. Similarly, it may not be possible to accurately model a large change in a single regulated market using partial equilibrium analysis" (U.S. EPA, 2010a). While a general equilibrium approach is recommended in these cases, how to determine what constitutes a large number of sectors or in which types of sectors a large change in a single market may matter from a general equilibrium perspective is left to the analyst.

The literature offers little additional guidance. Kokoski and Smith (1987) find that while a partial equilibrium model adequately captures welfare effects for a fairly large single sector shock (up to a 42 percent unit cost increase), use of this approach to analyze a small multi-sector shock results in large

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[19] Another well-studied program is the 1990 Clean Air Act Amendment SO_2 cap-and-trade system for power plants. Chan et al. (2012) note that research finds it spurred improvements in scrubber performance, the use of different mining techniques to extract low-sulfur coal, and blending of low and high-sulfur coal.

[20] Technological change also is widely accepted to be one of the most critical, albeit less understood, factors that determine future levels of GHG emissions and the associated cost of reducing them (Jacoby et al, 2006).

errors in welfare relative to a fairly simple, highly aggregate CGE model. The size of the error is related to the direction and magnitude of the relative price change in the directly regulated sector compared to other consumer goods. For instance, while the partial and general equilibrium models produce estimates of similar magnitude for price changes in the directly and indirectly affected sectors for the small multi-sector policy shock, the direction of the price changes differ, amplifying the disparity of effects across sectors.

Pizer et al. (2006) find that reduced-form sector representations in a CGE model and partial equilibrium sector models that hold input prices and output constant result in similar predictions of emissions responses to a carbon price in the commercial building, industrial, and household transportation sectors. This is not the case in the electricity sector where a substantial portion of emission reductions stem from reductions in output, particularly as marginal costs of achieving reductions rise. However, the partial equilibrium and general equilibrium approaches produce markedly different estimates of the marginal welfare cost in all four sectors. They are "about $10 to $15 per ton of carbon higher than costs measured by the permit price in the building and electricity sectors, $10 per ton lower in the industrial sector and $50 per ton lower in household transportation." The main reason for the differences in estimates is the presence of pre-existing taxes in these sectors.[21]

We also researched whether other Federal agencies offer specific guidance on how the number or type of sectors analyzed affects model choice. The International Trade Commission, which uses both partial and general equilibrium approaches to evaluate the effects of changes in trade and non-trade barriers, highlights a particular challenge when using general equilibrium models to analyze policy changes in a narrowly defined industry. Using the example of studying the effects of removing a tariff from the frozen bakery product sector (standard industrial classification (SIC 2053), they note that, in the CGE model, "frozen bakery products are included together with several dozen other slightly related but not identical industries. For example, bottled and canned soft drinks (SIC 2086), cereals (SIC 2043), and chewing gum (SIC 2067) are included in the combined sector of 'food products.' Thus, the frozen cake industry may be too small a part of the model's food products sector to give meaningful results due to 'aggregation bias.' Put another way, there are too many products in the model's sector to accurately isolate the frozen bakery products industry. To study a narrowly defined industry, the partial equilibrium model would be a better choice" (Rivera 2003). (The economic impacts white paper will discuss how aggregation issues affect an analyst's ability to adequately estimate sectoral effects from regulation.)

5. Sensitivity of Social Cost Estimates to Model Structure

This section considers the sensitivity of cost estimates to a number of key issues associated with the structure of CGE models as identified in the charge. Each factor is evaluated with regard to how it may affect the technical merits of using a CGE model for estimating the social cost of an air regulation. The specific factors examined are:

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[21] The commercial buildings and electricity sectors have relatively high indirect business taxes; the industrial sector has relatively low indirect business taxes; household transportation is not covered by the income tax on capital.

- Sensitivity of CGE models to key parameter assumptions;

- Static versus dynamic model structure (including degree of model foresight);

- The rules used to close a model (i.e., government revenue-expenditure, savings-investment, current account);

- How international trade is represented (e.g. when a detailed representation of the U.S.' main trading partners may be important);

- Whether transition or adjustment costs are incorporated into the model for some input markets;

- Considerations relevant to the availability and cost of an economy-wide model versus alternative modeling approaches (i.e., to inform analytic choices that weigh the value of information obtained against analytic expenditures when resources are constrained); and

- How technological change is captured in the model.

Evidence of the sensitivity of social cost estimation to these factors is gathered mainly from the existing literature. Given that most of the relevant literature in this area is not specific to the analysis of environmental regulation due to the dearth of papers focusing on that topic in a CGE context, this section draws from a broader array of CGE modeling experience (e.g. in international trade settings). The intention of this section is not to ask panelists to review/critique past modeling approaches used by the EPA or outside groups but rather to summarize the different approaches pursued to-date to set the stage for the broader discussion of these issues as laid out in the charge.

5.1 Sensitivity of Results to Parametric Assumptions

Model structure and parameter assumptions have long been recognized as important drivers in applied CGE analysis. Of particular interest are estimates of elasticities that help define potential production processes and agent preferences, as model results are often highly sensitive to these parameters.[22] For instance, Shoven and Whalley (1984) observe that results from CGE analyses of the U.S. tax system are sensitive to labor supply, saving, and commodity-demand elasticity assumptions. Fox and Fullerton (1991) find that estimates of welfare changes associated with tax reform are more sensitive to assumptions about the elasticity of substitution between labor and capital than the actual level of detail about the U.S. tax system in the model. More recently, Elliot et al. (2012) confirmed that CGE analysis is likely far more sensitive to uncertainty around elasticity parameter assumptions than other data inputs such as the benchmark social accounting matrix.

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[22] See section 5.5 for a discussion of sensitivity of results to Armington trade elasticity assumptions as well as calibration versus econometric estimation in this context.

The sensitivity of CGE model results to parameter values has been the subject of much discussion given the common approach of selecting values through a calibration process (Hansen and Heckman, 1996).[23] However, selecting econometrically estimated parameter values from the literature is not without its own concerns due to inconsistencies between the structure of the CGE model and a large range of potentially contradictory empirical analyses that provide elasticity estimates (Shoven and Whalley, 1984; Canova, 1995).[24] To address these concerns, some researchers have chosen to econometrically estimate the parameters of their model in a framework that is structurally consistent with the CGE model (e.g., Jorgenson et al., 2013).

To better understand the implications of uncertainty around parameters to which modeling results might be sensitive, researchers also have considered different approaches for characterizing the range of changes that might be induced by a policy shock. For instance, some cases studies have relied on basic comparative statics, or slightly more involved sensitivity analysis. However, it has been noted that varying only one, or a few, parameters at a time could potentially provide an incomplete characterization of the uncertainty surrounding the results due to important interactions between parameters within complex and highly non-linear CGE models (Abler et al., 1999). Therefore, researchers also have considered more formal approaches to accounting for uncertainty by defining probability distributions over parameters and integrating over the distributions using Gaussian Quadrature to obtain mean values for the results (e.g., Hertel et al., 2007) or Monte Carlo simulations to obtain sampling distributions for the results (e.g., Selin et al. 2009). (The uncertainty white paper will include a more complete discussion of approaches to characterizing uncertainty in the results of applied general equilibrium analysis, including additional approaches such as inter-model comparisons, and validation and verification exercises.)

5.2 Static vs. Dynamic Models

Static CGE models represent a snapshot of the economy in one year. A new equilibrium solution represents the full impact of the policy relative to the base-year economy, even though this impact may be expected to occur over a period of several years. Static models may therefore be misleading with regard to the social cost of environmental regulation if they vary over time. Static models have also been criticized for their inability to model saving and investment decisions, which by their very nature reflect tradeoffs in consumption over time (Pizer and Kopp, 2005). This could be an important consideration when a regulation is expected to have a potentially large effect on investment behavior.

Dynamic CGE models may solve a system of linked static equilibrium models, which retain the assumption that consumers are myopic and therefore view returns to capital as fixed, or may meet market conditions and budget constraints in every period simultaneously (Pizer and Kopp, 2005). For instance, a recursive dynamic model (e.g., the Emissions Prediction and Policy Analysis (EPPA) CGE model) solves each time period individually, and agents make decisions based only on prices in the current period (Paltsev et al.,

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[23] CGE models typically calibrate structural or behavioral parameters so that the model is able to reproduce the social accounting matrix, which "records all the transactions and transfers between production activities, factors of production, and agents in an economy" (Arora 2013).

[24] Shoven and Whalley (1984) note that CGE modelers "typically place] a lot of reliance on literature surveys of elasticities and, as many of the modelers have observed ..., it is surprising how sparse (and sometimes contradictory) the literature is on some elasticity values."

2005). In a forward-looking model (e.g., IGEM and EMPAX-CGE), representative agents maximize utility over all periods simultaneously, according to a constant intertemporal elasticity of substitution and a budget constraint.

These assumptions influence the transition path that the economy will take as it moves to a new equilibrium after a policy shock. Because recursive dynamic models assume fully myopic economic agents firms and consumers do not anticipate future changes to the economy or regulatory setting, and do not make investments or change consumption and savings behavior until the period when the change takes effect (Paltsev and Capros, 2013). In forward-looking models, economic agents have perfect foresight; they know exactly what will happen in the future and can therefore incorporate this information into current decisions (Paltsev and Capros, 2013).

It is also worth noting that a dynamic model can represent a steady-state equilibrium with a constant growth rate, or a baseline forecast taken from economic projections generated by external sources.

Model Foresight in Dynamic CGE Models

There are a number of analytic implications tied to the degree of model foresight assumed in a dynamic CGE model. For instance, a recursive dynamic model may lead to higher estimates of compliance costs and welfare impacts compared with a forward-looking model since it restricts response flexibility.[25] However, in cases where circumstances prevent agents' from having perfect foresight, a forward-looking model may lead to underestimates of the compliance costs and welfare impacts of regulation. Note that many EPA regulations phase in standards or allow for intertemporal smoothing of compliance (e.g., borrowing and banking of emissions allowances) that could alleviate this concern in many instances.

Due to computational limitations, the large number of variables and constraints that are solved simultaneously in a forward-looking model may restrict the level of detail that can be included in each period compared with a recursive dynamic model.[26] These details may include greater disaggregation of industries, households, and regions, as well as vintages of capital and advanced technologies. In some cases this additional detail, for example technology representation, may be critical to adequately assessing the welfare effects of a regulation.

Forward-looking models also introduce additional closure requirements, most notably with respect to the terminal conditions required to ensure that the necessarily finite implementation of the model provides an adequate approximation of behavior in the infinite horizon problem. The common approach to approximating an infinite horizon solution in a forward-looking model is to require that the economy be on a balanced growth path in the final year, where the growth rates of consumption and investment are equal (Lau et al., 2002).

Babiker et al., (2009) compare recursive dynamic and forward-looking versions of the EPPA CGE model. While the authors attempt to keep the two versions as similar as possible, the details must be simplified

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[25] Air regulations may cause firms to invest in compliance equipment, energy efficient technologies, or process changes gradually in advance of regulation, which then may result in changes in prices before it takes effect.
[26] It is also worth noting that both forward-looking and recursive-dynamic models can include resource depletion, but forward-looking models better represent intertemporal extraction decisions.

in each time period to accommodate the forward-looking framework (mainly focused on the representation of vintaged capital and energy technologies). They also consider different versions of the forward-looking model that vary the time horizon, numbers of regions, and technologies to investigate the importance of these assumptions. As expected, they find that the forward-looking model - which allows the economy to adjust in anticipation of policy and smooth impacts over the entire model horizon – achieves compliance with the climate policy at a lower welfare loss than the recursive dynamic version of the model. However, they find that the difference is small: while consumption smoothing in the forward-looking version reduces welfare impacts, its relative lack of resolution with regard to energy technologies works in the opposite direction.

In a similar exercise (also using recursive dynamic and forward-looking versions of EPPA), Gurgel et al. (2011) find similar results, with lower welfare losses in the forward-looking version. However, Gurgel et al. (2011) find these differences to be non-trivial: the forward-looking model results in welfare changes that are, in some cases, over 50 percent lower than those of the recursive dynamic model. In one case the choice of model structure flips the sign on the welfare change.

Recursive-dynamic and forward-looking CGE models both make strong assumptions about expectations – either no foresight or perfect foresight. Hybrid dynamic approaches have been developed to represent expectations that lie between these two bounding cases. These hybrid models can potentially increase the level of detail that is included in each period compared to a perfect foresight model while also capturing a more realistic representation of forward-looking behavior compared to a recursive dynamic model. For example, Dixon et al. (2005) describe an iterative solution process for introducing rational expectations into a recursive model. This algorithm iterates to find equilibria between each period and the one following, where a model period may represent one or more years.

5.3 Closure Rules

In any economic model, choices must be made about which variables to make exogenous and which to make endogenous. There must be enough independent equations in the model to explain all of the endogenous variables. The choices made in determining which variables are exogenous and which are endogenous can define the direction of causality in the model and the interpretation of the effects of a policy shock. Choices made for particular components of a model are called "closure rules."[27]

Microeconomic closure refers to closure rules for factor markets. A common factor market closure allows factor prices to adjust to keep the market in equilibrium (often referred to as "neoclassical" closure). Alternatively, for the labor market, the wage could be made exogenous and the level of employment endogenized.

Macroeconomic closure refers to closure rules for the three macroeconomic balances included in most CGE models: savings-investment, government revenue-expenditure, and the current account. For the savings-investment closure, a number of alternatives are possible. In an investment-driven closure, real investment is fixed and the savings rate adjusts endogenously to match the level of investment. Alternatively, with a savings-driven closure, the savings rate is fixed and investment adjusts. (Rattso (1982)

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[27] This discussion is based in large part of Gilbert and Tower (2013), Chapter 26 "Closure."

demonstrates the sensitivity of CGE model results to the method of savings-investment closure chosen.) Government revenues and expenditures can similarly be balanced in a number of ways. Real government expenditure – purchases of goods and services and transfers – can be fixed, with a tax rate or rates adjusting so that revenues match expenditures. Alternatively, tax rates can be fixed and the level of purchases and/or transfers can be endogenous. As its determinates are considered to be outside of the scope of most CGE models, the current account is generally fixed.

The appropriate choice of closure rules is dictated largely by the nature of the policies being analyzed. Choosing appropriate closure rules can avoid misleading attribution of causality. For example, for welfare analysis with a static model, an appropriate closure may be to fix investment, government purchases, and the current account, so that intertemporal adjustments that are outside the scope of the model do not influence policy impacts on household welfare.

5.4 International Trade Representation

Environmental policy has the potential to change prices throughout the economy, including the relative prices of traded goods across regions. Changes in the prices of imported goods and foreign demand for exports have implications for consumer welfare (Hillbury and Hummels, 2013). We briefly summarize three key aspects of trade representation in CGE models: the extent to which a model explicitly represents trade via regional disaggregation, and its treatment of exchange rates and the balance of payments, and use of Armington assumptions.

Explicit Representation of Trade

CGE models vary widely in how explicitly they represent international trade. A single-country CGE model focused on the U.S. economy – while it typically includes multiple economic sectors – often represents trade in a highly simplified, aggregate way. For instance, EMPAX-CGE and USREP represent the United States as a large open economy, with a single "rest of world" Armington import supplier for each good, and export demand elasticity representing international trade. In EMPAX-CGE, foreign and domestic import varieties of a good are combined in a CES function according to the Armington elasticity of substitution. This approach averages out the trade response for all other countries into a single rest of world region, which may reduce the accuracy of trade results.

Likewise, the real exchange rate for foreign goods can be flexible or fixed in a CGE model (Burfisher, 2011). A flexible foreign exchange rate is determined by supply and demand for foreign exchange derived from import and export markets. Alternatively, the exchange rate can be fixed and serve as the model numeraire. The EPPA model uses a flexible exchange rate, as it models multiple large international regions. Likewise, ADAGE is a global model that allows changes in policy to impact world prices. In contrast, single-country CGE models such as IGEM and EMPAX-CGE assume world prices are not affected by changes in U.S. policy. They use a fixed exchange rate, so trade quantities change according to the Armington price relative to the exchange rate numeraire. Using a flexible exchange rate allows for changes in the real prices of imports instead of just quantity effects. As a result, changes in import and export quantities are smaller in models such as ADAGE compared to models such as IGEM. Likewise, to the extent that a model assumes U.S. policies increase world prices of affected commodities, the relative price difference between

goods produced in the U.S. and goods produced abroad will be lessened. This will reduce the negative impact on exports and reduce the import substitution effect, both of which are driven by the relative price differential (U.S. EPA, 2010b).

Another key assumption is the ability of regions to access international capital markets. The modeler can assume that the level of the international balance of payments (BOP) remains relatively constant over the model period, or that the region is able to change its level of borrowing over time. The total debt over the model horizon may be assumed constant, so that additional borrowing must be repaid by the end of the model period, or the balance of payments can be flexible. For example, in EMPAX-CGE the intertemporal balance of payments must remain constant over the model horizon, but borrowing is possible between periods (U.S. EPA, 2008c). In contrast, in USREP the balance of payments deficit is constant in all periods (Rausch et al., 2009). McDaniel and Balistreri (2003) examine the sensitivity of results to the treatment of balance of payments in a CGE model. They compare a case in which there is no change in the balance of payments in each period, a case with flexible BOP in each period but a fixed BOP over the model horizon, and a case with perfect capital markets. While the solutions to these cases converge in later years, they find that the adjustment in early periods varies with each balance of payment assumption.

Armington Trade Assumptions

Data reveal that trade between countries often occurs in both directions for the same good, known as "cross-hauling." To preserve this bilateral trade, CGE models often use the Armington (1969) assumption that versions of a single good from different regions of origin are imperfect substitutes. The elasticity of substitution between domestic goods and varieties of imported goods is known as the Armington elasticity (i.e., it is a fixed taste parameter in a CGE model). This elasticity determines the import demand functions for each good and region.

Hillberry and Hummels (2013) note that trade-focused CGE models typically borrow Armington trade elasticities from the empirical literature while calibrating taste and technology parameters. However, they often combine econometric estimates that are based on different data sources, empirical approaches, and time horizons.[28] Single-country CGE models typically do not explicitly model production and demand in other countries. Instead, they often rely on a reduced-form approach to parameterize exports to and imports from the rest of the world without directly tying them to specific econometric estimates (Hillberry and Hummels, 2013).

While single-country CGE models use a simplified approach, it is still possible for the Armington elasticity to vary between sectors, and for some goods to rely on assumptions other than Armington trade. For example, in the EMPAX-CGE and EPPA models crude oil is treated as a homogeneous commodity and has

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[28] Hertel et al. (2007) identify three problems with commonly used Armington trade elasticities from the literature that can result in overly sensitive welfare estimates: point estimates are used without consideration of the precision of the estimates; most studies ignore variations in quality between different import varieties; and aggregation is often different between econometric estimates of elasticities and CGE models. The authors evaluate the effects of establishing a free trade agreement using consistently estimated trade elasticities and their standard errors to account for uncertainty in the underlying parameters. Because they generate a distribution of model results they are able to construct confidence intervals around their welfare estimates.

one world price. The EPPA model treats natural gas as either Armington, regionally homogeneous, or globally homogeneous in different model versions.

One disadvantage of the Armington approach, as McDonald and Balistreri (2003) point out, is that modeling a small economy (in their example, Colombia) with more aggregated trading partners results in the focus country's goods having market power in each region's import demand function. This assumption can result in policy scenario optimal tariffs that are quite sensitive to the Armington elasticity. In other words, the aggregated trading partners specified in the model may not substitute away from Colombian goods as easily as they could in reality because there is a specific demand for Colombian products in the Armington trade function. Another limitation of models that use the Armington formulation is that trade in each good cannot occur between countries that do not trade that good in the base year (Zhai, 2008).

An alternative to the Armington specification is the Melitz specification, which allows firm heterogeneity; trade patterns are no longer dictated by an exogenous taste parameter but by factors such as market size, technology and trade barriers. However, the Melitz specification is still relatively rare in applied work.

5.5 Modeling Technological Change in CGE Models

The treatment of technological change in economy-wide models remains a difficult challenge (Jacoby et al, 2006). The traditional and widely used approach is to treat technological change as exogenous. One way to operationalize this concept is to model technological change as a function of time such that it tracks the overall progress of the economy. Another approach that is commonly used in CGE models assumes that improvements in technology evolve over time in a way that reduces energy use via autonomous energy efficiency improvement (AEEI) parameters (McCracken et al, 1999).

A common application of exogenous technological change in CGE models relates to the availability of backstop technologies for carbon policy. These are energy sources that are already known but not yet commercially viable (e.g., advanced solar power, nuclear fusion, advanced fossil-fuel generation). It often is assumed that a backstop technology is available in an unlimited supply at a constant but relatively high, marginal cost. If the price of energy inclusive of carbon policy becomes high enough, the backstop technology will penetrate the market and prevent the price of energy from rising further. Modelers often assume that the cost of the backstop technology is decreasing with time at its own autonomous rate (Jacoby et al, 2006; Sue Wing, 2006a). Some models have more than one backstop technology (Burniaux et al. 1992; Paltsev et al., 2005).

Many researchers and policy makers have found the treatment of technological change as exogenous rather unsatisfactory because it does not account for how changes in relative prices or the policy being analyzed may influence technological change (e.g., Popp, 2005). This has led to the development and incorporation of endogenous (emission-reducing) technological change in some CGE models via feedback mechanisms that influence the direction, pace and magnitude of change (Sue Wing, 2006a). Conceptually, it is not entirely clear how the feedback between policy and technological change should work. As a result, researchers have pursued a wide array of approaches.

It should be noted from the outset that these approaches do not typically make all technological change in the model endogenous. Technological change is only modeled as endogenous for certain industries,

while it remains exogenously determined for other sectors. For example, CGE models designed to evaluate environmental –mainly, carbon - policy often allow endogenous technological change in most of the energy sectors while technological change in other sectors usually follows the rate of change in the overall economy, which is exogenously determined (Clarke et. al, 2006).

Gillingham et al. (2008) classify endogenous technological change into three distinct types: price-induced, research and development (R&D), and learning-by-doing.[29] Price-induced technological change occurs when changes in relative prices promote innovations that help reduce the use of an expensive input (e.g., when an increase in the price of energy increases energy efficiency). To the extent that environmental regulations affect relative prices, they may be one source of price-induced technological change (Clarke, et. al, 2006). In applied work, such changes in efficiency are captured through a productivity parameter that is linked to prices (Newell, 1999).

The IGEM CGE model captures the possibility of price-induced technological change. Translog price functions for each sector are differentiated to arrive at estimable input share equations that are a linear function of input price and a latent variable that represents biased technological change (Jorgenson et al., 2013). The bias parameters indicate a change in the share of input use over time while holding input prices constant. The translog price and input share equations are estimated using data for 35 sectors to shed light on the relative contribution of price-induced and autonomous technological change in the U.S. Such a detailed estimation of technological change sets the IGEM model apart relative to most CGE models that use benchmark data to calibrate these parameters.

A second approach to endogenizing technological change allows for investment in research and development (R&D) to influence the level and direction of technological change in the economy. However, most applications of endogenous technological change induced by investment in R&D still assume it occurs outside of the model. [30] Goulder and Schneider (1999) use a CGE model to illustrate how R&D induced technological change affects the appeal of carbon abatement policies. R&D is allowed to spillover (reduce costs or increase productivity) to other firms within the same sector but not across sectors in their model. They find that induced technological change without spillovers "implies lower costs of achieving a given abatement target, but it implies higher gross costs of a given carbon tax." With spillovers, whether or not R&D results in lower costs of achieving a particular emissions target depends on how they vary across sectors.

A third possibility for introducing endogenous technological change into a CGE model is to incorporate learning-by-doing (i.e., the cost of using a technology is a decreasing function of experience with that technology (Popp et al., 2010)). Because learning-by-doing is often applied to a particular technology,

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[29] Clarke et al. (2008) add spillovers as a distinct source of endogenous technological change, while Gillingham et al (2008) consider them as part of R&D.

[30] Sue Wing (2006a) uses a theoretical model to show that, while an environmental tax always biases production away from the dirty good towards the clean good, this does not necessarily imply that the environmental tax biases innovation via R&D towards the clean good. He also notes that there is the potential for policy-induced technological change to crowd out R&D in other, non-emission reducing areas, though evidence indicates that the impact of crowding out is small.

however, it is often more straight-forward to include learning-by-doing in a detailed sector model than an economy-wide model (Gillingham, 2008; Pizer and Popp, 2008).

5.6 Transition or Adjustment Costs

As previously stated, BCA typically focuses on comparing social costs and benefits of various regulatory options in the new equilibrium (i.e., once all adjustments in prices and quantities in the economy have occurred) compared to the previous, baseline equilibrium. However, there may be cases – for instance, during periods of sustained unemployment in the overall economy – when adjustments to the new regulation do not occur frictionlessly and therefore real social costs are incurred in addition to those already accounted for in the long run. A key question is to what degree an economy-wide model can capture these types of transition or adjustment costs adequately. This section attempts to characterize a CGE model's abilities in this regard. An accompanying memo explores whether other types of economy-wide models aside from CGE are potentially able to include transition costs as a component of their measures of social cost.

CGE models traditionally focus on medium or long run equilibrium, when most inputs are free to adjust and consumers are allowed to modify purchasing and labor-leisure decisions in response to new prices. A longer time horizon also affords greater opportunities for firms to change their production processes (i.e., to innovate). However, given this focus as well as the typical assumption of instantaneous adjustment of markets to the new equilibrium many CGE models do not account for adjustment costs. This is particularly true of static models, which offer only a snapshot in time.

Because dynamic models have more explicit representation of the capital stock, some may include a transition path as the economy adapts to a regulation. There are two main approaches to modeling the capital stock in dynamic CGE models, referred to as "putty-putty" and "putty-clay." Models that use the "putty-putty" approach assume an undifferentiated capital stock that moves instantaneously (and therefore costlessly) between sectors of the economy. In contrast, models that represent capital using a "putty-clay" approach assume capital stocks that are specialized. In this case, a regulation where new equipment is needed to meet emission requirements will result in transition costs as outdated technology is retired and replaced or as capital is moved across sectors (Pizer and Kopp, 2005). For example, in the recursive dynamic USAGE ITC model (Dixon and Rimmer, 2002), the rate at which investment occurs is limited within the capital supply functions to represent caution on the part of investors. By contrast, in the forward-looking EMPAX-CGE model, capital adjustments are limited by quadratic functions that increase the cost of producing new capital as more is produced in a given time period.[31]

With regard to the labor market, the default assumption in CGE models is an economy with full employment, where any net changes in employment levels are associated with voluntary changes in

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[31] In addition, Harris (1984) introduces price-setting and market power into a CGE framework. Some CGE models used for trade policy analysis also include imperfect competition due to economies of scale (Swaminathan and Hertel,1997; Harrison, Rutherford and Tarr, 1997).

leisure.[32,33] However, several CGE models have been modified to accommodate factor market rigidities. For example, the MIRAGE and LINKAGE models include minimum wage as a basic feature of labor markets (Banse et al, 2013). Banse et al (2013) also propose including an empirically estimated upward sloping labor supply curve as a solution to better represent the more nuanced nature of labor markets.[34]

To our knowledge, relatively less attention has been paid to incorporating labor market adjustment costs into CGE models for purposes of analyzing the effects of domestic environmental regulation, though there are a few exceptions. For example, USAGE, a dynamic single-country U.S. CGE model, allows for potential disequilibrium in the labor market by specifying three labor market states: employed, unemployed, and not in the labor force where employed labor is differentiated by industry, occupation, and region. Labor is not perfectly substitutable across all categories. For instance, those employed in occupations with less similar characteristics required more training than those employed in occupations with similar characteristics. The model also assumes a cost associated with changing employment states (Dixon and Rimmer, 2002). Thus, it is possible that "not everyone is doing what they want to do at the going wage rates. Some new entrants and unemployed people who offer to work in [a particular sector] cannot find a job, and some employed people [end up] working in another activity" (Dixon et al., 2011).

Recent work has focused on revisiting the assumptions of full employment and instantaneous adjustment in labor markets using highly aggregate CGE models. Shimer (2013) develops a simple two sector general equilibrium model with one clean and one polluting good, and search unemployment to characterize the optimal tax rate on the dirty good. Adjustment costs accrue as labor is reallocated across sectors in response to the tax, which influences the mix of clean and dirty goods produced and consumed. Hafstead and Williams (2014) also develop a simple two-sector (one clean and one polluting) CGE model that allows for involuntary unemployment due to search frictions. They find that, on net, employment effects of an environmental tax are small; while employment falls in the polluting sector, this is offset by an employment gain in the non-polluting sector.[35] They note, however, that this result may be sensitive to the nature of pre-existing distortions in the labor market. Using a one-sector growth model, Rogerson (2015) finds that explicitly accounting for labor market transitions to a new equilibrium makes little

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[32] As the EPA's Economic Guidelines point out, "this does not mean, of course, that specific individual workers are not harmed by a regulation if they lose their jobs" (U.S. EPA, 2010a).

[33] Note that the treatment of employment impacts in BCA is a matter of ongoing debate. Typically, BCA focuses on overall efficiency – how aggregate benefits compare to aggregate social costs. Impacts on specific sectors, for instance the labor market, are generally subsumed within the broader measures of social costs and benefits; transfers between economic actors are netted out. Thus, we focus on labor market effects that represent additional real costs – for instance, adjustment costs – not already accounted for in a long run social cost estimate.

[34] There also appears to be a relatively recent international trade literature that pairs empirical estimates of worker transition costs between sectors in specific countries with dynamic, structural GE trade models. The cost of switching from one sector to another is high (e.g., the few estimates available for the U.S. range from two to six times the average annual wage); workers frequently switch sectors in spite of these costs due to unobserved factors unrelated to wage differentials. Because labor markets are slow to respond to changes in relative wages, researchers find adjustment costs may contribute significantly to the welfare effects associated with liberalizing trade. See Riker and Swanson (2015) for a review of these papers.

[35] There is a growing literature on the distribution of social cost of regulation – including its potential effect on workers –, that will be discussed in the economic impacts white paper.

difference to the overall welfare effects that result from regulation, though he also notes that this is a function of the transition dynamics assumed in the model. Slower transition dynamics would widen the gap between social cost measures with and without this transition.

5.7 Relative Availability and Cost of CGE Models

The first CGE model was developed by Leif Johansen in the 1950s. Early CGE models were mostly coded in FORTRAN, often by programmers rather than by the model originators. By the 1980s, several software packages had been developed that simplified the development of CGE models and led to their increasingly widespread usage. In the mid-1970s, the GAMS programming language was developed at the World Bank for solving large-scale, non-linear optimization problems and was later adapted to CGE modeling. Around the same time, the GEMPACK software package was developed specifically for solving CGE models. In the mid-1980s, Tom Rutherford developed MPSGE, which operates as a subsystem within GAMS and, among other features, simplifies coding of the CES production and consumption nests commonly used in CGE models.[36] Neither GEMPACK nor GAMS/MPSGE are available for free.

In addition to the software for running the models, CGE models require consistent data sets. In the early days of CGE modeling, modelers usually had to compile their own data sets from disparate sources. This was time consuming, error prone, and made it difficult to compare the results from different models. Fortunately, a number of efforts have reduced the data compilation requirements for CGE modelers. On the international front, the Global Trade Analysis Project (GTAP), based at Purdue University, has been developing and selling consistent international data sets for over 20 years. The current version of the data base, GTAP 8, with base year 2007, includes data on production, consumption, energy use, and international trade for 129 regions and 57 commodities. GTAP produces corresponding static and dynamic CGE models, coded in GEMPACK. For the U.S., the IMPLAN Group, LLC develops and sells data sets in the form of input-output tables and social accounting matrices at the national, state, and county levels that can be adapted for CGE models. Tom Rutherford has developed programs that can process GTAP and IMPLAN data for models programmed in GAMS and MPSGE, which are available for free.

Specially designed software and the availability of consistent data sets have considerably reduced the barriers to entry for CGE modeling, though a high level of technical expertise is still required to operate a CGE model and, in particular, to understand when a model is working as it should and how to appropriately characterize model results. Furthermore, as highlighted throughout this paper, a number of methodological, structural, and data challenges associated with building or utilizing a CGE model remain when applying them to the analysis of air regulations.

In addition, while a CGE model could provide insights into the broad economic impacts of an air regulation, it may not have the detail needed for more specific policy analysis. Single-country CGE models of the United States that have been linked to detailed sector models and then used for the analysis of specific U.S. environmental policies are described in Section 7.2. Models like these require a more significant investment and greater skill in programming complex regulations and in interpreting the results.

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[36] For additional detail on GAMS, GEMPACK, and MPSGE see Horridge et al. (2013).

Single-Country CGE Models of the United States

Table 7 lists some characteristics of the six most common single-country CGE models used to estimate the costs of U.S. environmental regulations. All of the models in the table are dynamic. Regional coverage ranges from the national-only focus of IGEM to the 51 regions (50 states and the District of Columbia) in the USAGE-R51 model. USAGE-R51 also has the greatest sectoral coverage with 497 sectors. Although several of these models are relatively new (US REP, US-REGEN, NewERA), they all have deep roots in previous generations of models.

Table 7: Characteristics of U.S. CGE models

MODEL	DEVELOPER	# OF U.S. REGIONS	# OF SECTORS	FORWARD LOOKING	LINKED TO SECTOR MODEL	PUBLICALLY AVAILABLE?
EMPAX-CGE	EPA	5	35	X		Yes (source code only)
IGEM	DJA	1	35	X		No
US REP	MIT	12	11		X	No
US-REGEN	EPRI	15	9	X	X	No
NewERA	NERA	11	12	X	X	No
USAGE-R51	CoPS	51	497			No

Note: This table was compiled from available documentation which is more complete for some models than others. Alternative versions of some models may have different numbers of regions and sectors.

Four of the six models (EMPAX-CGE, IGEM, US-REGEN, and NewERA) assume perfect foresight. The other two models (US REP and USAGE) are recursive dynamic. Three of the models (US REP, US-REGEN, and NewERA) are linked CGE-electricity sector models based on the work of Böhringer and Rutherford (2009). One feature that distinguishes IGEM from the other models in the table is that all of its parameters are empirically estimated from a sectoral time series data base that spans almost 50 years (Jorgenson et al., 2013). Other models mainly parameterize their models based on the literature and expert judgement.

In general, the models emphasize different features and no one model contains all features that may be desirable for all types of analyses. For example, in addition to some of the differences already discussed above, US-REGEN does not model tradeoffs between labor and leisure and would therefore exclude social costs associated with tax interaction effects; nor would it be able to analyze impacts on labor supply. IGEM and some versions of US REP include heterogeneity across households on the basis of income and other socioeconomic characteristics. While less relevant for the analysis of social cost, this level of detail may be important when considering economic impacts.

All of the models in Table 7 are proprietary, although the EPA has posted the source code for a version of EMPAX-CGE (U.S. EPA, 2013a).[37, 38] In the past, the EPA has used EMPAX-CGE and IGEM to analyze air regulations. As a result, the EPA has put both of these models through an independent peer review (U.S. EPA, 2006; U.S. EPA, 2010b).

6. Characterizing Economy-Wide Social Cost and U.S. CGE Models

This section discusses and compares the types of outputs often used to characterize economy-wide social cost (e.g., equivalent valuation, household consumption, GDP, etc.) and their potential relevance with respect to characterizing changes in economic welfare.

The Office of Management and Budget's Circular A-4 (2003) states:

> "Both benefits and costs are measured by the value that individuals place on the change resulting from a particular regulatory alternative. This value is typically and most easily measured in terms of the amount of money the individual would pay ("willingness to pay" (WTP)) or require as compensation ("willingness to accept" (WTA)), so that the individual is indifferent between the current state of the world (baseline), on the one hand, and the consequences of the regulatory alternative along with the monetary payment, on the other hand."

When measuring aggregate social costs, economists often estimate equivalent variation (EV) or compensating variation (CV). Both of these are monetary measures of the change in utility brought about by changes in prices and incomes, and focus on changes in consumer welfare rather than on changes in total final demand (U.S. EPA, 2010a). The difference between them depends on whether the change is assumed to occur (EV), or whether it is not yet in place (CV). For instance, EV measures what a consumer would be willing to pay to avoid an increase in prices (and thus, a decline in real income) resulting from a regulation going into effect. In contrast, CV measures how much a consumer would need to be compensated to accept changes in prices and income such that the consumer achieves the same level of utility experienced prior to the policy shock.

CGE models use a number of metrics to report economic costs associated with a policy shock.[39] Because changes in consumer welfare encompass more than just market activities – for instance, there is a monetary value to leisure – welfare changes (without accounting for social benefits) are typically

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[37] The GAMS MPSGE source code does not include the data required to run the model.
[38] EPA guidance states, "To promote the transparency with which decisions are made, EPA prefers using nonproprietary models when available. However, the Agency acknowledges there will be times when the use of proprietary models provides the most reliable and best-accepted characterization of a system. When a proprietary model is used, its use should be accompanied by comprehensive, publicly available documentation." See http://www.epa.gov/crem/cremlib.html for more information.
[39] Also of interest are the effects of regulation on prices and production in specific economic sectors. The economic impacts white paper will discuss issues related to deriving energy price and sectoral impacts from CGE models.

measured as changes in EV.[40]   Changes in household consumption are also typically reported by CGE models, though this measure omits consideration of how the introduction of a new policy affects leisure. In the context of a carbon tax or cap-and-trade policy, the change in consumption is usually larger than the change in consumer welfare "because an increase in the price of consumption (due to an increase in energy prices) leads to a reallocation of time to non-market activities" (Paltsev et al., 2009).[41] In other words, reductions in time worked are offset by increases in leisure time. The extent to which EV and consumption measures differ depends on what is assumed about the responsiveness of labor supply to changes in wage rates (i.e., if labor supply is completely inelastic, these measures do not differ) (Paltsev and Capros, 2013).[42]

Conceptually, it should be noted that a welfare measure of the social cost of a regulation is generally not the same as a change in gross domestic product (GDP). GDP is defined as the sum of the value (price times quantity) of all market goods and services produced in the economy and is equal to Consumption (C) + Investment (I) + Government (G) + (Exports (X) – Imports (M)). As a measure of economic activity, it should be immediately evident from the definition that it is not the same as consumption and also misses effects on leisure. When a model incorporates environmental quality, a welfare measure also captures changes in the value of nonmarket goods, while GDP does not.

Paltsev et al. (2009) show that the cost of meeting targets consistent with an 80 percent reduction in U.S. GHG emissions by 2050 is lowest when measured in terms of EV, followed by consumption, and finally GDP. GDP impacts are larger due, in part, to double counting. For instance, reductions in investment due to the policy are counted as part of the I component of GDP in the year they occur, but decreases in future consumption that result from the decline in the capital stock are counted again in the C component of GDP in future years. The prospective study of the effects of the Clean Air Act Amendments from 1990-2020 (U.S. EPA, 2011a) found a similar trend (see Figure 6). However, Paltsev and Capros (2013) note that the direction of the difference between effects of a policy as measured by GDP versus consumption varies with time period and scenario in some models.

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[40] We focus on EV as a measure of economic welfare in the subsequent discussion, not because it is necessarily the preferred metric but because it is more commonly reported by CGE models.

[41] Paltsev et al. (2009) also note that changes in consumption are higher than changes in welfare when measured in percentage terms because the denominator is total consumption, which excludes the value of leisure.

[42] McClelland and Mok (2012) find that empirical estimates of compensated labor supply elasticity range from 0.1 to 0.3. A previous review of the literature found a range of 0.2 to 0.4 (CBO, 1996). U.S. CGE models vary in the value used but are at or above the top end of the range found by McClelland and Mok. For instance, NewERA uses 0.25, USAGE-ITC uses 0.3, and EMPAX-CGE uses 0.4. IGEM empirically estimates compensated elasticity of labor supply as part of its model of household behavior and finds a value of 0.7 (Jorgenson et. al 2013). The economic impacts white paper will include a more detailed discussion of labor supply in CGE models.

Figure 6: Social Cost Measures vs. GDP Effects of Clean Air Act Amendments: 2010 - 2020 (Percent Change)
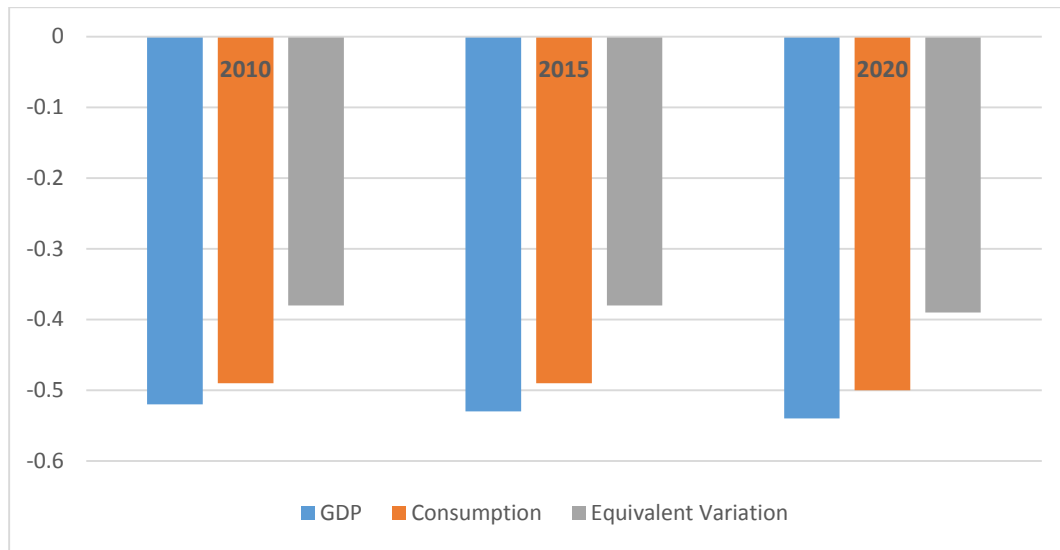
<div align="right">Source: (U.S. EPA 2011a)</div>

Thinking through how the components of GDP may be affected by a policy shock highlights why using changes in GDP as a proxy for the welfare effects of a policy is potentially problematic.[43] For instance, as previously described, a regulation that requires firms to invest in new capital in a given year will see a large increase in the I component of GDP. However, capital also affects the availability of goods and services that can be consumed over a much longer time period (which is also captured in C), inflating the GDP measure relative to welfare due to double counting. In addition, certain types of investments are excluded from economic welfare but included in the standard measure of GDP. For example, a central role of government is to provide public goods (e.g., roads, bridges, environmental quality) and to redistribute income across households (e.g., social security, Medicare) through transfer payments. As defined by OMB (2003), transfer payments are "monetary payments from one group to another that do not affect total resources available to society." Thus, changes in G are excluded from the welfare measure of a policy. Finally, changes in the terms of trade (which measures how many foreign goods can be purchased for a given amount of U.S. dollars) are more relevant when measuring effects on household consumption than the change in the quantity of net exports (X – M). If consumers can afford to purchase fewer foreign goods with a given amount of income after the introduction of a regulation, this is equivalent to a reduction in real income. Thus, while changes to trade patterns due to a policy shock may be reflected in both GDP and welfare measures, they are not necessarily equivalent measures (Paltsev et al., 2009; Paltsev and Capros, 2013).

More recently, some have suggested that changes in net employment may be an important additional measure of a policy's overall effect on economic welfare.[44] Rogerson (2015) notes that an economy-wide

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[43] Because GDP is viewed as a relatively poor indicator of social welfare, there is an active discussion of ways to move national account metrics closer to a measure of well-being (e.g., Stiglitz et al., 2009; Fleurbaey, 2009).

[44] Note that a potential loss in employment within the regulated sector does not capture the possibility that these jobs are made up in other parts of the economy.

model that explicitly accounts for the labor market already incorporates employment effects into its welfare calculation through changes in how the household values consumption and leisure in the utility function. For instance, in the case where a policy lowers employment, it also likely lowers output and consumption but increases leisure. The only way to weigh the cost of lower consumption against the benefit of higher leisure is through a utility function that explicitly values both. Rogerson goes on to observe that this need not apply only to a model with full employment and no price rigidities. With less than full employment due to a pre-existing wage rigidity, the model will reflect that leisure is valued less than employment by households. When Rogerson (2015) examined whether welfare calculations in a highly stylized model are affected by assumptions about how quickly the labor market responds to a policy shock, he finds that the size of the labor response has little effect. This is because of the offsetting effects on leisure already noted above.

Figure 7. Time Profile for Economic Welfare, GDP, Consumption, and Employment Relative to Reference for Central Cap and Trade Case
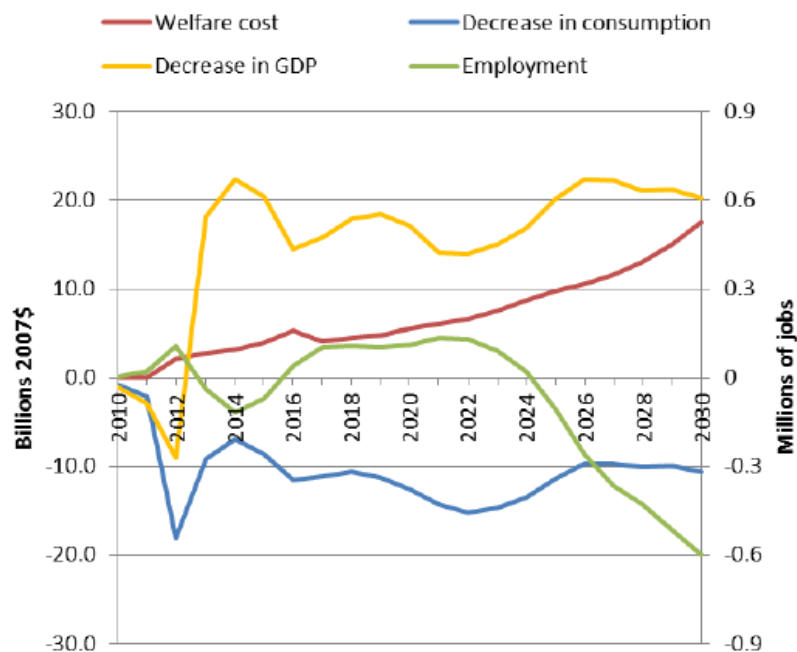
Source: Krupnick and McLaughlin (2011)

Krupnick and McLaughlin (2011) also show that there is little direct correspondence between economic welfare and alternative measures such as GDP, consumption, and employment for the carbon and energy policies they analyze (Figure 7 shows one illustrative example). They note a number of reasons why using employment as a measure of welfare is problematic. First, the number of people employed in the economy is a measure at a given point in time (a stock concept) while GDP and welfare costs are designed to represent the accumulation, depreciation, or depletion of a stock over time (flow concepts). With flow measures, an analyst can sum the changes in welfare or GDP for each year of the policy (discounted appropriately) relative to the baseline and interpret it as the effect of the policy on that metric. However,

it becomes problematic to apply the same technique to a stock concept (i.e., add up changes in the number of jobs over time due to a policy shock). Krupnick and McLaughlin (2011) give the example of one job created in the first year but not subsequent years of a 20 year policy, which shows up in the model as a new job in each and every year. If these changes are then added up over time, it appears as though the policy creates 20 jobs, when in fact it still only represents a single job created. Second, a count of how many people are employed may not be indicative of increasing prosperity or economic growth. For example, if workers largely stay employed but take pay cuts during an economic downturn, this would not be reflected in an employment measure. In this case, changes in the total wage bill (number of jobs times the wage rate) may be a more appropriate metric for capturing effects in the labor market. It is worth noting, however, that such measure indicate more about the distributional impacts of a policy its overall effect on welfare. (The economic impacts white paper will discuss what types of labor market effects can be identified and reported by a CGE model.)

7. Linking CGE and Sector Models

CGE models allow an analyst to capture economy-wide interactions of producers and consumers as changes in prices and quantities in the regulated sector, resulting from compliance with the regulation, percolate through the rest of the economy. However, they are highly aggregate representations relative to a detailed, technology-rich engineering or partial equilibrium model. In particular, CGE models usually do not have detail on specific methods of compliance that may be important when analyzing the social costs of an air regulation. Of key interest to the EPA is whether it is possible to reflect this heterogeneity in compliance strategies and their accompanying costs in a CGE framework. One avenue for doing so is through the explicit linking of CGE and sector-specific models.

Focusing on energy-environmental policy analysis, Hourcade et al. (2006) propose a three-fold rule-of-thumb by which to judge the appropriateness of a model. First, the model should have an explicit treatment of technology. Second, the model should include realistic microeconomic behavior. Third, the model should have macroeconomic feedback mechanisms that link energy demand and supply to changes in rest of the economy. CGE models include the latter two features, but they typically lack critical technological detail for energy systems. CGE models typically capture the economic cost of technological adaptation to energy policy through substitution elasticities. This approach, however, rests uneasy with energy sector experts. According to Böhringer (1998), this group of analysts favors "partial equilibrium activity analysis models which provide a precise technological description of the energy system." This approach accommodates the first requirement identified by Hourcade et al., but while it boasts of rich detail, it fails to address how the energy system interacts with the rest of economy. Linking CGE and detail sector models has the potential for producing an approach that satisfies all three of the features Hourcade et al. identify as important for environmental policy analysis.

This section discusses the main conceptual methodologies for linking sector and CGE models, describes the linking approaches taken in the three single-country U.S. CGE models in Table 7 that link to a sector model (US-REGEN, US REP, and NewERA), describes several linking applications in the economics

literature in the context of the electricity and transportation sectors, and discusses some of the practical challenges of linking models to analyze air regulations.

7.1 Linking methodologies

Interest in linking CGE and detailed sector models arose in part because of the very different results that emerged from partial equilibrium or "bottom up" models (e.g., energy sector) and general equilibrium or "top down" (e.g., CGE) models in early analyses of policies to mitigate climate change (Wilson and Swisher, 1993; IPCC, 1996). CGE models typically have highly aggregate representations of the energy sector, with continuous, separable nested constant-elasticity of substitution (CES) production functions. Calibration exercises require specifying elasticity of substitution parameters, but empirical estimates are rare at the level of aggregation required in a CGE model. In addition, the two types of models often reflect very different priors about how technological change and substitution possibilities occur. According to Böhringer (1998), the elasticities of substitution that determine the potential costs of technology adoption in a CGE model are so abstracted from reality that they limit the extent "to which empirical evidence on substitution patterns can be incorporated." Partial equilibrium approaches do not suffer from a lack of detail; for instance, there are a number of models with technology rich representations of the energy system (i.e., including processing, transport, distribution, and final energy production) that reflect the range of fuels, capacity, and other characteristics of generating units; installation, operation, and maintenance costs for an individual technology; and constraints faced by units based on load, transmission, and regulatory concerns. However, energy demand is often specified in a very reduced-form way (e.g., not by customer type) and other markets that might be affected by an environmental policy's effect on the energy system are not considered.

Thus, much could be gained if these two modeling approaches could be linked to one another in a coherent and sensible way to take advantage of "the technological explicitness of bottom-up models with the economic richness of top-down models" (Böhringer and Rutherford, 2008). There have been myriad attempts at doing so. Below, we describe soft linking, full integration (sometimes referred to as hard-linking), and the wide range of approaches that fall somewhere in between below.

Soft linking of models

Soft linking typically refers to the passing of information between existing CGE and detailed sector models that have been independently developed and where the models stay completely separate. Information flows may be one-way or two-way.[45] Two-way flows may also be iterative in an attempt to achieve consistency between the solutions. However, because the models have been developed independently, there are often inconsistencies in behavioral assumptions and accounting concepts between them that can be difficult to reconcile, making it challenging to achieve "overall consistency and convergence of iterative solution algorithms" (Böhringer and Rutherford, 2008).

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[45] EPA's linking of the EMPAX-CGE model with the linear programming model of the electricity sector, Integrated Planning Model (IPM), for the analysis of some air regulations is an example of a one-way soft linking approach (see section 7.5 for a discussion of some of the challenges EPA has encountered when using this type of approach).

In general, to better harmonize scenarios and specifications across CGE and detailed sector models that are soft linked requires a formalized system to determine common points where the models overlap. Wene (1996) suggests using the Reference Energy System (used to link the MESSAGE III bottom-up energy system model and the ETA-MACRO top-down economy-wide model). Krook Riekkola et al. (2013) demonstrate a highly systematized process of soft linking models in an analysis of Swedish climate policy (i.e., linking the TIMES energy system model and EMEC CGE model of the Swedish economy).

One possible advantage of soft linking models is that developers of the individual models, who are expected to have superior knowledge of them, have more control over how the models are used. In addition, Martinsen (2011) describes soft linkage approaches between large models as advantageous because "the complexity and running time generally is manageable," and there is transparency at each iteration in the linkage.

Full integration of models

Hard linking of models implies the complete integration of a CGE and detailed sector model within one consistent framework. This has a number of distinct advantages over soft linking including a potentially more rigorous connection of the models and the ability to solve the system more rapidly, which is particularly advantageous when running multiple simulations. In a comparison of soft-linking and full integration of an energy system model and a forward-looking dynamic growth model, Bauer et al. (2008) find that another advantage of full integration is that it ensures that the capital market is in equilibrium, which is not the case with the soft linked version of their models.

Although the potential for consistent estimation through hard linking is attractive, attempting to hard link a CGE model to a large, highly detailed sector model increases the dimensionality of the model, making it difficult to solve (Lanz and Rausch, 2011). For that reason, initial work explored hard linking small scale economy-wide models to larger energy sector models (an early example of full integration is the MACRO dynamic aggregated growth model and the MARKAL energy system model by Manne and Wene (1992)).

Another approach to hard linking is to fully integrate the CES production and consumption structure of a CGE model with an activity analysis model of the energy system as a mixed complementarity problem (MCP). The MCP approach "provides a general mathematical format that covers weak inequalities, i.e. a mixture of equations and inequalities, and complementarities between variables and functional relationships" that allows the modeler to overcome problems of model integration in a consistent way (Böhringer and Rutherford, 2009). In particular, it allows for the representation of tax distortions and the dependence of demand on prices as well as factor incomes in optimization problems (Böhringer and Rutherford, 2008). However, practical applications of full integration are still limited due to the complexity of the mathematical algorithm and the inability to apply it when the detailed sector model includes upper and lower bounds on many decision variables (Böhringer and Rutherford, 2009). Examples of the MCP full integration approach include Böhringer (1998), Frei et al. (2003), and Böhringer and Rutherford (2008).

Other linking approaches

In between these two book ends — soft linking and full integration — are a wide range of hybrid approaches to linking models that have one common feature: they all explicitly incorporate detail from one model directly into the other. These approaches range from the relatively simple incorporation of a few details from one model directly into the other to a relatively sophisticated passing back and forth of information between models to converge to a solution. However, it is important to note that throughout much of the literature, the hybrid linkage approaches that have been implemented are frequently idiosyncratic in that they are conducted within the context of a specific application from which it is often difficult to generalize lessons to other settings. Sue Wing (2006b) notes that, in spite of a growing literature, this approach is still in its infancy: "Perhaps the most important reason is the difficulty involved in constructing databases which integrate macroeconomic data with engineering detail in way that facilitates simple calibration of hybrid models."

Generally, explicit incorporation of some details from one model into the other involves representing a subset of the technological richness from a sector model directly in a CGE model. For instance, McFarland et al. (2004) present a methodology for incorporating bottom-up carbon capture and sequestration (CCS) technologies into the dynamic CGE model, EPPA. One of the key challenges they encounter is ensuring that economic modeling of the technologies remains consistent with the basic laws of thermodynamics throughout the simulations. To incorporate a detailed representation of electric generation technology into a CGE model, Sue Wing (2008) develops a social accounting matrix (SAM) based structure for combining multiple, incommensurate sources of economic and engineering data. Kiuila and Rutherford (2013) apply this approach to carbon abatement technologies.

As previously mentioned, though the potential for consistent estimation through hard linking is attractive, dimensionality problems often arise when attempting to link detailed sector models to CGE models. To overcome this challenge, Böhringer and Rutherford (2009) developed a technique to decompose an integrated MCP model (discussed above) and solve it iteratively. Complementarity methods are used to solve the top-down CGE model and quadratic programming is used to solve the underlying bottom-up energy (supply) model. In an energy context, electricity supply in the CGE model is treated as exogenous and replaced by the detailed sector model. This is accomplished by first solving the CGE model given net electricity supply (and economic rents) from the sector model. The sector model is then solved based on locally calibrated prices for electricity from the CGE model to derive a new estimate of net electricity supply. This new estimate from the sector model is then used to solve the CGE model anew. The process continues until convergence between the two models is achieved. As long as the energy sector is small in value terms relative to the rest of the economy, the iterative algorithm converges rapidly. Böhringer and Rutherford's decomposition technique has been used to solve a number of linked CGE-energy sector models. Examples using single-country U.S. CGE models are discussed in the next section.

7.2 U.S. CGE models linked with energy sector models

Three of the six U.S. CGE models described in Table 7 — U.S REP, US-REGEN, and NewERA — have been linked to a detailed linear programming model of the energy or electricity sector using the Böhringer and

Rutherford (2009) decomposition technique described above. In the cases of U.S.-REGEN and NewERA, the CGE and sector models are designed by the same institution with the explicit goal of linking them to each other. This section briefly summarizes the details of how these paired models work and any issues encountered when linking them, to the extent they are discussed in the literature.

US REP Model

The US Regional Energy Policy (US REP) CGE model has been linked to two different highly detailed partial equilibrium linear programming models of the U.S. electricity sector.[46] Lanz and Rausch (2011) link a static version of US REP to a static version of the MARKAL energy systems model (developed by the International Energy Agency), while Rausch and Mowers (2014) link a recursive dynamic version of US REP to the Renewable Energy Development System (ReEDS) model (developed by the National Renewable Energy Laboratory).[47]

Before applying the Böhringer-Rutherford decomposition technique, the authors calibrate the CGE and electricity sector models to the same benchmark. This is achieved when electricity sector outputs and inputs from the sector model are consistent with the aggregate representation of the electricity sector in the CGE model's SAM. The decomposition technique is then applied to analyze the policy scenario by passing information back and forth between the US REP CGE model, parameterized with benchmark input demand from the electricity sector model and assuming electricity generation in US REP is exogenous, and the electricity sector model where electricity demand and fuel supply are linearized to locally approximate the prices and quantities from the CGE model. The models are repeatedly solved, updating the relevant prices and quantities, until the results from the two models converge. Lanz and Rausch (2011) define convergence as a difference in variables of less than one percent between iterations.

Lanz and Rausch (2011) note that one element of complexity when iterating between the models is the difference in how demand is specified. US REP models annual electricity demand, while MARKAL subdivides it to better represent variation in demand by season and load block (ReEDS divides up demand similarly). In the benchmark, since electricity demand in the sector model is taken directly from the CGE model's SAM, they simply share it out across seasons and load blocks. In applying the decomposition technique, they scale demand and prices in the electricity sector model to match those in the CGE model when passing information between models.

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[46] Recall that US REP is a regional, recursive dynamic CGE model of the U.S. economy including nine household income classes, 10 commodities, and 12 U.S. regions.

[47] The MARKAL model identifies the least-cost way to meet electricity demand where each generator is characterized by a constant marginal cost and maximum generating capacity in each time period. The model includes information on capacity, generation technology, operation and maintenance costs, fuel costs, and energy sources for over 16,000 electricity generators in 2006. Annual demand for electricity is subdivided into load blocks over time. ReEDS finds the least-cost way to meet demand through the expansion of electricity generating capacity and transmission based on installation and operating costs over a 20 year time horizon. It includes detailed representations of electricity generators for conventional and renewable technologies and resources, transmission accessibility and costs, and multiple spatial regions. Annual electricity demand in ReEDS is differentiated by season and load time. The model assumes that all markets are competitive.

Rausch and Mowers (2014) describe a few other modifications they make when linking US REP to the ReEDS model. To incorporate a demand response into ReEDS, they modify its objective function to maximize producer plus consumer surplus, instead of minimizing total cost. They also utilize an aggregation procedure to map the highly disaggregated geographical regions in ReEDS to 12 US REP regions when passing prices and electricity demand between the models. Finally, because resource constraints in ReEDS allow low-cost producers to capture economic rents they must then be distributed to resource owners in the US REP model. The rents are distributed to household groups in US REP based on capital income shares from the National Income and Product Accounts.

US-REGEN Model

The US Regional Economy, Greenhouse Gas, and Energy (US-REGEN) model is a linked CGE-electricity sector model built by the Electric Power Research Institute (EPRI).[48] As previously mentioned, it is solved iteratively using the Böhringer-Rutherford decomposition technique. Specifically, information on regional electricity generation and consumption, fuel consumption, and electricity prices (as well as carbon prices when relevant) are iteratively passed back and forth between the two models until convergence is achieved. In each iteration, equilibrium electricity and input prices and demand for electricity from the CGE model are entered as exogenous inputs in the electricity sector model. The electricity sector model then solves for the quantity of electricity supplied/consumed in each region and time period as well as fuel and input demand. The information on electricity supply from the sector model is then fed back into the CGE model (i.e., is treated as exogenous). Fuel and input demand are also treated as fixed in the CGE model. The CGE model is then solved for a new set of equilibrium prices and electricity demand. Quantities and prices are iteratively passed between the electricity sector and CGE models until convergence between them is achieved, which is defined as less than one percent between iterations for all regional prices and quantities (de la Chesnaye, 2013).

One unique aspect of the US-REGEN model that is not reflected in other linked US CGE modeling approaches discussed in this section is that not all regions are assumed to be perfectly competitive; some of them use average, rather than marginal, cost pricing for electricity (also referred to as cost-of-service). This complicates the passing of prices between the CGE and electricity sector models because the marginal cost faced by producers is not necessarily the same as the price that consumers pay for electricity – the consumer price also includes a capital recovery charge. The model takes advantage of the iterative nature of the solution algorithm between models to account for non-competitive pricing. Once the electricity

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[48]Blanford et al. (2012) and de la Chesnaye (2013) describe the US-REGEN CGE model as a dynamic, forward-looking model with 15 regions and nine sectors, five of which are related to energy. Consumers of electricity do not buy energy directly from the energy sector. Energy prices are first translated from wholesale to retail by the addition of a margin, representing the services needed to deliver energy to the customer. Energy purchases are then converted into energy services that include the capital used to produce the service. This allows for energy efficiency improvements through substitution between capital and energy. The electricity sector model linked to the CGE model is a detailed linear programming model of electric generating capacity and dispatch decisions across load segments. It also has 15 regions. In response to demand, the model determines whether to carry forward, retrofit, or retire existing capacity and when to invest in new capacity subject to a number of constraints such as renewable portfolio standards requirements and transmission constraints between regions.

sector model finds the least-cost dispatch solution, the cost-of-service prices are computed by summing the fuel and operating costs with a base rate for capital recovery based on depreciation of new and existing capital. This price is then passed to the CGE model as the price that consumers face. When the CGE model passes information back to the energy model, it uses the stored marginal cost data from the previous run as the electricity price along with new information on electricity demand. Thus, while the two models report different prices for electricity, electricity demand converges based on cost-of-service pricing (Blanford et al., 2012).[49]

NewERA Model

NERA Economic Consulting has relied on an integrated CGE-electricity sector model[50] to produce a number of applied analyses of environmental policy (e.g., NERA 2013).[51] As with the other linked U.S. CGE models, a consistent benchmark is first established. The electricity sector model is solved based on an initial forecast of electricity demand and prices, which are then passed to the CGE model. The CGE model then solves for baseline prices and quantities in all sectors while constraining energy prices and demand to match the electricity sector model (i.e., they are treated exogenously in the CGE model).

When evaluating the effects of a policy, the electricity sector model solves for equilibrium quantities (demand, supply, and inputs required) and then passes these quantities to the CGE model, which solves for equilibrium prices and quantities in all markets. The CGE model then, in turn, passes regional electricity and fuel prices (and in cases where there are permits, carbon prices) back to the electricity sector model. Taking these prices as exogenous, the electricity model then solves for the new equilibrium quantities. This process of passing quantities to the CGE model and prices to the electricity sector model continues until there is convergence in the results. NERA defined convergence as differences in prices and quantities between the two models of less than a fraction of a percent.

7.3 Comparisons of simulations with hybrid and component models

A number of policy simulations have used a linked, hybrid model and then compared the same simulation using either the original model, in the case of a modified top-down CGE model, or the component models, in the case where separate bottom-up sector models and top-down CGE models have been linked. We summarize results from some of these exercises below.

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[49] Blanford et al. (2012) also note the importance of ensuring that capital payments in the electricity sector model do not violate zero-profit conditions in the CGE model (e.g., purchases of clean energy credits by fossil-fuel dependent regions from renewable-abundant regions).

[50] NERA's CGE model is a dynamic, forward-looking model with 11 sectors, 5 of which are in energy, and 12 regions. Its electricity sector model is also a dynamic, forward-looking model but has 23 U.S. regions. As with the other electricity sector models discussed in this section, it is a linear programming model that minimizes costs over the time horizon of the model subject to a number of constraints on transmission, demand (including peak demand), fuel availability, and emissions. In addition to the electricity sector, it also models the coal sector. Each of the more than 17,000 electricity generating units in the model can add retrofits, build new capacity, switch fuels, or retire units in response to policy. They can also modify decisions about when and how often to run units.

[51] Tuladhar et al., (2009) uses a previous version of the linked model, MRN-NEEM, to evaluate climate policy. The model functioned in much the same way as NewERA and contained similar features.

In order to incorporate a detailed representation of electric power technology in a CGE model, Sue Wing (2008) develops a SAM-based structure for combining multiple sources of economic and engineering data. Sue Wing (2006b) compares this hybrid CGE model, incorporating the detailed representation of the electricity sector, with the same CGE model when the electricity sector is represented in a conventional top-down manner. Simulations are of a tax on CO_2 emissions ranging in increments from $50 to $200 per ton. For abatement up to about 30 percent from baseline emissions, welfare losses, as measured by EV, are greater with the top-down model than with the hybrid model. However, for abatement levels greater than 30 percent welfare losses are greater with the hybrid model. For all levels of abatement, GDP losses are greater with the hybrid model. Sue Wing attributes the greater costs in the hybrid model to the discretization of the hybrid model's electric sector production function, which reduces aggregate input substitutability, and the imperfect malleability of technology-specific capital, which limits the adjustment of generating capacity. A key parameter is the elasticity of capacity adjustment, which represents the ease of retrofit or retirement of technologies in the short run in the model.

Lanz and Rausch (2011) compare simulations of a linked CGE-energy sector model to its component top-down and bottom-up models. The benchmark model is a static version of the US REP CGE model linked to an electricity sector model. The stand-alone CGE and electricity sector models share common technological features and are calibrated to the same benchmark equilibrium. They simulate a national tax on CO_2 emissions ranging from $25 to $100 per ton. Comparing simulations across the stand-alone electricity sector model and the integrated model reveals that, for the same CO_2 tax, the electricity sector model appears to overestimate electricity price increases but underestimates reductions in electricity demand and electricity sector emissions. This results from the inability of the partial equilibrium model to capture changes in the slope and position of the electricity demand schedule. This is true even when the partial equilibrium demand curve is calibrated to the CGE model. Comparing simulations across the integrated model and the stand-alone CGE model, the stand-alone CGE model tends to overestimate emissions reductions for the same CO_2 tax and underestimate welfare costs for the same level of abatement (note, however, that comparisons are more region specific than in the stand-alone electricity sector-integrated model comparison). The authors point out that while it may be technically possible to mimic the bottom-up response to policy shocks in a top-down model through calibration of the nesting structure and elasticities, this is particularly difficult when multiple regions are specified.

Rausch and Karplus (2014) extend the USREP-ReEDS linkage described in Rausch and Mowers (2014). They model a Clean Energy Standard (CES) and Renewable Portfolio Standard (RPS) using the USREP model alone and with the linked model. The USREP model includes one renewable technology – wind – along with other advanced fossil and nuclear technologies as backstop options as described in Böhringer (1998). The ReEDS model includes detail on solar and geothermal technologies that enter into the RPS scenario. The authors find that the top-down model gives similar results to the linked model for the CES policy that relies on advanced fossil and nuclear options. However, the RPS allows certain types of renewable energy for compliance that are not represented in detail in USREP. The results from the US REP model alone differ significantly from the linked model that has more renewable technology detail. The authors suggest that additional renewable backstop technologies could be added to USREP to produce a top-down model that produces reasonable estimates of the impacts of the RPS policy.

Cai and Arora (2015) compare simulations with three different CGE models incorporating varying levels of electricity sector detail and substitution possibilities. All three models use the GTAP 8 database. Their benchmark model, CSIRO Trade and Energy Model (CTEM), includes 13 electricity generation technologies, including renewables and coal, oil, and gas with CCS. The technologies are combined through a Constant Ratios of Elasticities of Substitution, Homothetic (CRESH) function, which allows for differing levels of substitution between the individual technologies. For comparison, Cai and Arora construct another model, CTAP, that is identical to CTEM, but uses a single, aggregate electricity generation technology. There are two variants of CTAP. CTAP-0 has a Leontief specification that does not allow substitution between primary factors and fossil fuels, while CTAP-0.2 allows substitution between primary factors and fossil fuels, enabling the model to mimic movement toward clean energy sources in response to a policy shock. The authors impose carbon taxes such that the three models each achieve the same amount of cumulative emissions reductions. The average cost of attaining the reductions, as measured by the change in GDP, is almost three times higher for the CTAP-0 model than for CTEM. Costs with the CTAP-0.2 model are lower, but still almost twice as large.

Kiuila and Rutherford (2013) explore the integration of bottom-up abatement technology into a CGE model. They demonstrate two methodologies, the "traditional" and "hybrid" approach. In the traditional approach, the step curve from the bottom-up abatement cost model is translated into a smooth curve through a separate optimization routine. The results then are implemented in the CGE model as parameters. In the hybrid approach, similar to Böhringer and Rutherford (2008), the results from the bottom-up model are directly integrated into the CGE model using an activity analysis framework. For each of these approaches, Kiuila and Rutherford demonstrate two techniques – economy-wide and sector-specific – that endogenize abatement within a CGE model. In the former, the marginal abatement cost is applied to the whole economy; in the latter, the abatement processes are sector specific. The authors use a CGE model of the Swiss economy to simulate a carbon tax, focusing on the abatement potential for light duty vehicles. In contrast to other authors, they find virtually the same results with the traditional and hybrid methodologies when the same assumptions are applied.

7.4 Additional applications of model linkages

In previous sections we reviewed the range of methodologies that have been used to link top-down, economy-wide models and bottom-up, sector-specific models. We also described three U.S. CGE models that have been linked to electricity sector models and several studies that examine the sensitivity of results to use of a linked approach compared to a top-down or bottom-up model alone. In this section we briefly review several additional applications of model linkages not covered elsewhere that offer some insight into the way in which linkages between two or more models has been accomplished.

Carbon capture and storage

McFarland et al. (2004) add representations of three electricity generation technologies, two with CCS, to the EPPA model. These technologies produce lower carbon dioxide emissions than other conventional technologies, but are more costly and so do not operate in the baseline. The EPPA model uses nested CES production functions for renewable and nonrenewable electricity generation options. Conventional fossil

fuel generation is represented by one production function with additional functions for nuclear, hydroelectric, biomass and one function for wind and solar generation. These functions include AEEIs that represent exogenous technological advances over time.

Bottom-up information, taken from a technology study by David and Herzog (2000), is used to parameterize the nested CES production functions for the advanced generation technologies, using data on their costs, efficiencies, and emissions. Elasticities are chosen to restrict the input possibilities so that feasible energy balances are maintained under different scenarios. The production costs of these technologies are increased by a mark-up factor representing the difference in cost relative to the technologies that appear in the baseline. The entry of advanced technologies is controlled by the capital vintaging used by the EPPA model and by the addition of a fixed factor to represent the engineering capacity needed to install the new technology. By restricting the availability of this factor, the introduction of advanced technologies is slowed to a level that is more consistent with the observed path of new technologies entering the market.

Technology change

Martinsen (2011) links a CGE model of the Norwegian economy (MSG6) with a national MARKAL model and the global MARKAL Energy Technology Perspectives (ETP) model to investigate technology learning in the energy sector. Norway is included in a larger European region in the global ETP model. The global model has the ability to capture technology learning that is gained by worldwide innovation, which is then passed to the Norway MARKAL energy model. Global economic data from ETP is passed to both the Norwegian energy and economic models in a one-way soft linkage (the global model is only run once and Norway is assumed to be a price-taker that will not influence international results), while the linkage between the Norwegian models is established iteratively.

The model is calibrated to ensure that the MARKAL model baseline is consistent with the projections used by MSG6. Exogenous parameters for interest rates and economic growth in the national models are modified to match the global model assumptions. Imports and exports of electricity in the national models are assumed not to occur. Total factor productivity changes in the economic and energy models both include productivity changes due to technological change in the energy sectors, demand side energy efficiency, and structural change in the economy. To ensure consistency between the models and remove the possibility of double counting of productivity gains, the changes that contribute to total factor productivity are adjusted in both models.

Transportation

Schafer and Jacoby (2005) link the EPPA CGE model to a MARKAL transportation model. Transportation technologies are used directly by industry and households so a more detailed characterization is needed to retain the advantages of the bottom-up MARKAL model. Alternatively, a simple macroeconomic model could be added to the full bottom-up model, but this specification would ignore many of the industry linkages captured in EPPA. To link the EPPA and MARKAL models, a third module (referred to as the Modal Splits model) is added to disaggregate transportation in EPPA to the level used in MARKAL.

The authors simulate a Kyoto protocol target of a 7 percent emissions reduction in carbon dioxide below 1990 levels by 2010. The policy details are first introduced into EPPA to estimate economy-wide impacts. The resulting prices and transportation demand are then converted and disaggregated by the Modal Splits model. To link EPPA and MARKAL, some reconciliation is made between units used by the two models and their levels of aggregation. The EPPA model uses dollar values as units, while MARKAL uses passenger- and ton-kilometers. This conversion is done using the ratios from the benchmark year data and remains constant over all years. Transportation in EPPA is represented by transportation produced by households for their own use and by the transportation industry. Transportation industry output is then purchased by households and by other industries. Each of these three transportation categories is then scaled down to the transportation options in MARKAL, including personal automobiles of different types, passenger travel (air, bus, rail, etc.), and industrial transport (trucking, rail, water, etc.). To disaggregate household transportation into purchased transport and transportation provided by their own vehicles, a curve is fit to historical trends of the relative share of purchased transportation. The remainder is allocated to transportation from personal vehicles. These transport demands are then fed into MARKAL, which chooses the mix of transportation technologies that meet demand. This is a "one-way" soft linkage without iteration between the models from the CGE to the MARKAL model.

Several measures are taken to make the two models more consistent with each other. The elasticity of substitution between fuel and other inputs in EPPA is adjusted over time to reflect the technological change represented in MARKAL. To compute this elasticity over time, MARKAL simulations are run over different fuel prices for multiple years to determine the substitution possibilities that will be available in the future. Although elasticities in EPPA are updated based on these possibilities, the results do not perfectly match MARKAL output because of limitations of the CES functional form. The relative shares of transportation types are changed over time to reflect the MARKAL baseline. The discount rate in MARKAL is updated for consistency with EPPA. The AEEI factors in transportation are adjusted for consistency with technological change in MARKAL, for example MARKAL allows for technology improvements over time with constant fuel prices. The AEEI's are calibrated by iterating between the two models to find the energy efficiency improvement in EPPA that is consistent with MARKAL with constant fuel prices.

While CGE models use dollar values as the unit of measurement, for many energy policies physical quantities (e.g., miles per gallon) may be of greater interest. Karplus et al. (2013) use engineering data to calibrate the passenger vehicle sector in the EPPA CGE model to better account for physical units. The structure of the demand function is changed so that consumers demand vehicle miles traveled as a function of income and have a minimum number of miles required by the utility function.

Additional vehicle technologies are added to the model using the Böhringer (1998) approach. The bottom-up technology data is used to calibrate a description of new vehicles that have different characteristics in the way they combine capital with fuel to produce vehicle miles traveled. The elasticity of substitution is estimated by building up a marginal abatement cost curve for vehicle technologies, as in Dellink et al. (2004). This technology sector is hard linked into the EPPA model. Alternative fuel options that compete with gasoline vehicles are available and their characteristics are calibrated to engineering data.

7.5 Challenges and experience in linking models at EPA

The EPA has used a number of technology rich engineering and partial equilibrium models to forecast how compliance with an air regulation may occur and the expected cost of compliance. In this context, the way potentially regulated entities (e.g., new or existing, large or small sources) are expected to comply is of interest, and thus the details these models capture are useful.   This section describes possible methodological, data availability and organizational challenges when linking an engineering or partial equilibrium sector model with a CGE model. It is informed both by EPA's experience and the literature described in the previous sections. However, it is important to note that, in practice, any linking exercise is dependent on the information available from the sector model and the representation of relevant sectors and markets in the CGE model. As the bottom-up information and models available to the EPA differs significantly across regulations, any application of linking also may present unique challenges and considerations.

The EPA has some experience with linking a CGE model (EMAPX-CGE) to an electricity sector model (the Integrated Planning Model or IPM) to analyze air regulations using a one-way, soft-linkage approach.[52] (See the Appendix for a brief description of these and other models used by the EPA to analyze the costs of air regulations.) Briefly, IPM endogenously determines wholesale electricity prices, natural gas and coal prices within the contiguous United States. It has a rich representation of the requirements of air pollution regulations, compliance options, and facility operations. When linking IPM to a CGE model, the EPA has assumed that compliance costs from the electricity sector model are distributed across factors of production in the CGE model in a way that is consistent with historic data on the use of factors to control pollution in the sector (note that the regulation is modeled as a productivity shock). Another approach has been to use certain outputs from the electricity sector model, such as percent changes in wholesale electricity prices and changes in fuel prices, and impose these percent changes in the CGE model. This approach may conceptually be viewed as imposing wedges between producer and consumer prices of electricity and fuels.[53]

Linking an Engineering Model to a CGE Model

The EPA often uses an engineering approach to estimate the costs of air regulations. For instance, for stationary source regulations this type of approach might describe specific end-of-pipe or production process technologies that could be applied by regulated entities to reduce emissions as well as the cost to install and maintain those technologies (often inclusive of taxes but minus any reduced expenditures from changing production processes).[54] In other instances estimates of compliance costs may be based

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[52] While it is possible for the electricity demand and prices from EMPAX-CGE to be passed back to IPM and for the models to iterate to a solution that matches electricity and fuel prices and quantities across models, the EPA has not done this in the past due to the time and resources needed to perform sector and CGE model runs.

[53] We use IPM as an example because it has features that illuminate challenges to linking this type of model to a CGE model, it is well-documented, and it has been used often by the EPA to evaluate regulations. This is not to suggest that electricity sector regulations are necessarily good candidates for CGE analysis nor that the model is necessarily a good candidate for linking to a CGE model.

[54] The costs and performance of these technologies and techniques are often estimated specifically for the regulation and are often drawn from analyses of their application in practice and quotes from vendors.

on modeling representative facilities that capture relevant differences among the population of affected entities (if the operating and scale characteristics of the population of regulated sources are well-known). In some cases, engineering models may also attempt to identify the least cost option for the industry to achieve compliance. As described in Section 2.2, this approach usually does not account for potential changes in prices or production levels that could result from the regulation.

To link an engineering model with a CGE model, the accounting of outputs and inputs between the two models need to be sufficiently aligned. However, the composition of value-added and intermediate factors used to produce and install compliance technologies is not usually assessed in the studies that underlie the engineering model, making it less than straightforward to align these costs with national income accounts data. Furthermore, the composition of factors used in production may not be known a priori. Finally, to the extent that product qualities change, either intentionally via product standards or indirectly in response to the regulation of emissions from production, additional data or assumptions are needed to assign changes in expenditures from process changes to changes in the factors used by the regulated industry.[55]

Analysts also face the challenge of how to represent information about expected compliance in the CGE model's production functions. A detailed engineering model often provides information on the expected compliance behavior for each affected entity and its associated cost. The question then becomes how to aggregate this information up to the sector level for the purpose of linking to the CGE model.

Linking a Partial-Equilibrium Model to a CGE Model

Many of the challenges of linking engineering models to CGE models also apply to partial equilibrium models, such as how to align different underlying production technology representations, aggregation issues, and an incomplete and different accounting of outputs, inputs and pollutants across models. A further challenge of linking partial-equilibrium and CGE models is that they may have different baseline forecasts and elasticities of the demand and supply of various goods and factors that need to be reconciled. For example, when analyzing an air regulation using an engineering or partial equilibrium approach it is common to calibrate electricity demand to a forecast from a recent Energy Information Agency's Annual Energy Outlook, which may not be the same demand forecast used in a CGE model. Similarly, the partial-equilibrium and CGE models may have different demand and supply representations for these markets. For example, while many CGE models have aggregate representations of fuel supplies, IPM has detailed bottom-up representations of natural gas and coal availability, production costs, and transportation networks. It also captures heterogeneity in coal types including differences in characteristics that affect emissions (e.g., differences in chlorine content). The demand for factors used by these sectors need to be accounted for in the CGE model. Other differences may include what prices

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[55] It is also worth noting that a particular regulation may control multiple pollutants and polluting processes in a sector, which implies that multiple engineering models may be in use. Furthermore, a control technology that targets one pollutant may have a complex effect on the cost of controlling other pollutants. Capturing all of these changes simultaneously in a CGE framework, either through a hard or soft-linkage, also may prove challenging.

in those sectors might represent. For example IPM forecasts wholesale electricity prices, while a CGE model may be forecasting a retail electricity price.

Another potential complication when linking models is that partial equilibrium models attempt to capture certain behavioral responses to the regulation but not others. For example, IPM does not model the change in quantity demanded from changes in the supply of electricity (i.e., end-use electricity consumption is held constant). The CGE model considers the impacts of changing supply on quantity demanded across all sectors and households that use electricity. The general-equilibrium electricity sector results depend on the elasticities of demand with respect to price for all users. If there are meaningful changes in the quantity of electricity demanded as a result of a regulation, it may be desirable to conduct more than a one-way linkage. Another complication may be that in the partial equilibrium model abatement investments are incurred by existing units that are infra-marginal to determining an output price - existing electricity generating units earn rents – while the CGE model assumes perfect competition.

When limited years of compliance cost information is available from engineering or partial-equilibrium models, care also must be taken in distributing costs over time.[56] For instance, an electricity sector model such as IPM may consider the evolution of compliance costs over time, with EGUs entering and retiring from the market and capital investments over time. When using the partial equilibrium results as inputs in a CGE model, one must match the time periods between the two models. These time periods may not match up accurately, which then may require some degree of interpolated for each intermediate period.

To the extent that assumptions regarding how production or abatement technology costs change over time have already been applied in one of the models, another challenge is ensuring that assumptions regard technological innovation are consistent between the models. It is important that cost reductions are not applied to the same technologies twice, once in the partial-equilibrium model and again in the CGE model, as this could lead to an underestimation of the costs of the regulation.

Organizational Challenges to Linking Models

In addition to methodological and data challenges there are also potential organizational challenges with linking models. A sufficiently expert group is needed to develop and maintain each individual model. At EPA, engineering and partial equilibrium models are often developed by in-house engineers along with EPA contractors, who are able to assess the performance of abatement technologies and processes available to regulated entities. CGE models are often maintained and run by economists within or outside of EPA. Assuring that these models are linked appropriately may require engineers to be more familiar with CGE models and for economists to have a better understanding of sector-specific models.

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[56] A related issue is the end year of analysis. For example, some earlier versions of IPM do not run out to 2050, the last year in EMPAX-CGE. In this case, the final year costs are extrapolated to the end of the CGE period. In the past EPA has scaled the last year of available compliance costs from IPM to the value of electricity sector output in each baseline year. In other cases, only one or a select few years of compliance cost estimates are available. The same type of extrapolation may be necessary, with the specific adjustments based on the available information about the specific rule.

Another organizational challenge with linking models is having sufficient time and labor resources. Regulations are often developed over several years and are sometimes subject to statutory or court-ordered deadlines. Analyses are complex and involve coordination of many moving parts. While EPA experts stay current with developments in different sectors, a concerted data collection and model development effort is still often required prior to the preparation of a proposed rule. In addition to identifying modeling improvements after a rule is a proposed, stakeholders that comment on proposed rulemakings may identify compliance options or cost information that improves engineering or partial equilibrium estimates. The EPA may then find it appropriate to incorporate that information into a linked model, which requires more time and coordination.

8. Concluding Remarks

EPA has extensive experience using detailed engineering and partial equilibrium models to estimate the direct compliance costs of regulation. However, when the effects of an air regulation are expected to ripple throughout the economy these modeling approaches may misestimate social cost. CGE models capture such ripple effects but have been used less often by the EPA to analyze the social costs of air regulations. A fundamental question is, what's lost and what's gained by moving beyond an engineering and/or partial equilibrium approach to a CGE framework when estimating social cost?

This paper covers a wide range of topics in an attempt to inform this overarching question and to provide background relevant to other questions in the charge. In particular, this paper describes:

- The basic aspects of BCA as conducted by the EPA to estimate the social costs of air quality regulations, including the distinction between social costs and compliance costs;
- How social costs of air regulations are typically analyzed by the EPA, ranging from engineering to partial equilibrium to general equilibrium approaches;
- The range and complexity of EPA air regulations and the main challenges that may be encountered when attempting to represent them in a CGE model;
- How model choice may be affected by particular attributes of an air regulation as well as the structure and assumptions underlying a CGE model;
- The types of outputs often used to characterize economy-wide social cost and their potential relevance with respect to characterizing changes in economic welfare; and
- Ways to link CGE models with detailed sectoral models and practical challenges the EPA has encountered when attempting to link models in the past.

The EPA seeks guidance from the SAB Panel on how to weigh the technical merits and challenges of using CGE models when estimating the social cost of air regulations. Given heterogeneity across air regulations with regard to their attributes and main sources of uncertainty, it is likely that the modeling tools deemed most appropriate for cost estimation will be regulation-specific. For some regulations, an engineering or partial equilibrium approach may be adequate to capture the expected social cost. For other regulations, an economy-wide approach may add value over an engineering or partial equilibrium approach. However, the literature offers little specific guidance regarding what criteria to use to determine the choice of

modeling tools and the relative importance of different model attributes. There are many parameters and design features of CGE models that may have sizeable effects on social cost estimates. In addition, representing an air regulation in a CGE model may require a different approach than that used to model a tax. For instance, the analyst may need to understand how the anticipated methods of compliance match to sector inputs to production in a CGE model in order to represent compliance costs adequately. In addition, to adequately reflect heterogeneity in compliance options an analyst may contemplate linking economy-wide and sector-based approaches. However, again, the literature contains little guidance on how to address technical issues and challenges encountered in these instances.

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10. Appendix: Examples of Engineering, Linear Programming, Partial Equilibrium, and CGE Models Used by the EPA to Analyze Air Regulations

Control Strategy Tool (CoST)

CoST accomplishes two main tasks. First, it automates the key steps for identifying and applying control strategies applied to point, area, and mobile sources of air pollutant emissions. It currently contains control measure information for criteria pollutants, but does not contain any significant amount of control information for hazardous air pollutants or greenhouse gases. A control strategy is a set of control measures applied to emissions inventory sources in a specified geographic region (in addition to any controls that are already in place) to accomplish an emissions reduction goal. Such goals are usually for the purpose of improving air quality and/or to reduce risks to human health. The inputs to a control strategy consist of: a set of parameters that control how the strategy is run, one or more emissions inventory datasets, filters that determine which sources are to be included from those datasets; filters that determine which control measures are to be included in the analysis; and constraints that limit the application of measures to specific sources based on the resulting costs or emissions reduction achieved. The analyst has several choices regarding the algorithm used to determine how measures are assigned to sources. For instance, one algorithm assigns to each source the single control measure that provides the maximum reduction to the target pollutant, regardless of cost. Another algorithm assigns control measures to achieve a specified emissions reduction in a region while minimizing annualized cost.

Second, CoST calculates engineering costs associated with the control strategies that have been applied using one of two different methods: (1) an equation that incorporates key operating unit information, such as unit design capacity or stack flow rate, or (2) an average annualized cost-per-ton factor multiplied by the total tons of reduction of a pollutant. Most control cost information within CoST was developed based on the cost-per-ton approach because estimating engineering costs using an equation requires more detailed data, and parameters used in these equations may not be readily available or broadly representative across sources within the emissions inventory. The cost equations used in CoST estimate annual, capital and/or operating and maintenance costs and are used primarily for some larger sources such as industrial/commercial/institutional boilers and petroleum refinery process heaters.

CosT then produces a table that consists of emission source-control measure pairings, each of which contains information about the cost and emission reduction that would be achieved if the measure were to be applied to the source.

For more information, see the model documentation at: http://www.epa.gov/ttnecas1/cost.htm .

Optimization Model for Reducing Emissions of Greenhouse Gases from Automobiles (OMEGA) Model

The OMEGA model evaluates the relative cost and effectiveness of available technologies and applies them to a defined vehicle fleet in order to meet a specified greenhouse gas (GHG) emissions target. Presently, OMEGA models two types of GHGs, carbon dioxide (CO_2) from fuel use and refrigerant emissions from the air conditioning system. OMEGA is primarily an accounting model. While OMEGA incorporates functions that generally minimize the cost of meeting a specified emissions target, it is not an economic simulation model that adjusts vehicle sales in response to the cost of the technology added to each vehicle.

Because OMEGA is an accounting model, the vehicles comprising the vehicle fleet being evaluated can be described using a relatively few terms (i.e., vehicle's baseline emission level, the level of CO_2 reducing technology already present, and the vehicle's "type," which indicates the technology available for addition to that vehicle). Emission control technology can be applied individually or in groups, called technology "packages."[57] The user specifies the cost and effectiveness of each technology or package for a specific "vehicle type," such as midsize cars with V6 engines or minivans, in an Excel spreadsheet input file. The user can limit the application of a specific technology to a specified percentage of each vehicle's sales. The effectiveness, technology costs, and application limits of each technology package can also vary over time.

OMEGA considers which emissions technology to apply to a vehicle based on the cost of the technology at the consumer level, the value which the consumer is likely to place on improved fuel economy, and the degree to which the technology moves the manufacturer towards its emission target. Technology can be added to individual vehicles using one of several different algorithms. For instance, one algorithm considers only the cost of the technology and the value of any reduced fuel consumption considered by the vehicle purchaser. Another algorithm also considers the mass of GHG emissions reduced over the life of the vehicle in addition to costs and the value of fuel consumption. For each manufacturer, OMEGA applies technology to its vehicles until its sales-weighted GHG emission average complies with the specified emission standard or until all the available technologies have been applied.

One of the fundamental features of the OMEGA model is that it applies technology to a manufacturer's fleet over a specified vehicle redesign cycle. OMEGA assumes that a manufacturer has the capability to redesign any or all of its vehicles within this redesign cycle. OMEGA does not attempt to determine exactly which vehicle will be redesigned by each manufacturer in any given model year. Instead, it focuses on a GHG emission goal several model years in the future, reflecting the capability of mid to long term planning on the part of manufacturers. Any need to further restrict the application of technology can be effected through caps on the application of technology to each vehicle type.

For more information, see the model documentation at:
http://www.epa.gov/otaq/climate/models.htm.

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[57] For EPA's light-duty vehicle rules, individual technology direct manufacturing costs were estimated via vehicle and technology tear down, models developed by outside organizations, and literature review, while indirect costs were estimated using an indirect cost multiplier approach.

Integrated Planning Model (IPM)

The EPA often uses IPM – developed and run by ICF Consulting - to analyze the projected impact of air emission policies on the electricity sector. IPM is a multi-region, dynamic, deterministic linear programming model of the U.S. electric power sector that generates optimal decisions under the assumption of perfect foresight. It determines the least-cost method of meeting total energy and peak demand requirements for a region over a specified period. IPM provides forecasts of least-cost capacity expansion, electricity dispatch, and emission control strategies for meeting energy demand and environmental, transmission, dispatch, and reliability constraints. Costs are defined as expenditures by the electricity sector. When the cost of a regulation estimated using IPM is the difference in electricity sector expenditures between the baseline and policy case.

IPM can be used to evaluate the cost and emissions impacts of proposed policies to limit emissions of sulfur dioxide, nitrogen oxides, carbon dioxide, hydrogen chloride, and mercury from the electric power sector. IPM includes a detail-rich representation of emission control options encompassing a broad array of retrofit technologies along with emission reductions through fuel switching, changes in capacity mix and electricity dispatch strategies. It also captures interactions among the electricity, fuel, and emission markets. IPM represents power markets through model regions with distinct characteristics. These regions are largely consistent with the North American Electric Reliability Council assessment regions and with the organizational structures of the Regional Transmission Organizations and Independent System Operators, which handle dispatch on most of the U.S. grid.

IPM represents the least-cost arrangement of electricity supply (capacity and generation) within each model region to meet assumed future load (electricity demand) while constrained by a transmission network of bulk transfer limitations on interregional power flows. All existing utility power generation units, including renewable resources, are modeled, as well as independent power producers and cogeneration facilities that sell electricity to the grid. IPM provides a detailed representation of new and existing resource options, including fossil generating options (coal steam, gas-fired simple cycle combustion turbines, combined cycles, and oil/gas steam), nuclear generating options, and renewable and non-conventional (e.g., fuel cells) resources. IPM also incorporates a detailed representation of fuel markets and can endogenously forecast fuel prices for coal, natural gas, and biomass by balancing fuel demand and supply for electric generation. The model includes detailed fuel quality parameters to estimate emissions from electric generation. IPM provides estimates of air emission changes, regional wholesale energy and capacity prices, incremental electric power system costs, changes in fuel use, and capacity and dispatch projections.

For more information, see the model documentation at:
http://www.epa.gov/airmarkets/powersectormodeling.html .

Partial Equilibrium Analysis for Consumer Product Markets Affected by VOC Consumer Product Rule

The EPA constructed a partial equilibrium model specifically for use in the VOC Consumer Products Rule. Compliance costs associated with the regulation are expected to shift back the supply curve and therefore affect prices and quantities in each affected market, of which there are 23. The analysis assumes that the effects of the regulation in one market segment do not affect supply or demand in other market segments. The supply of consumer products is affected by the regulation in two ways: a firm can withdraw its product from the market or it can reformulate the product. Products that remain on the market are expected to see an increase in their costs of production due to regulatory requirements.

The supply shift due to withdrawal of products from the market is estimated by comparing estimated baseline profits to the projected cost of reformulation. The main case analyzed assumes that firms required a 10 percent profit margin to remain in the marketplace, though the EPA also examined scenarios with 30 percent and 50 percent profit margins.

For firms that reformulate their products, the shift in supply is simply the sum of each producer's new supply function, or marginal cost curve, which has shifted back due to the increase in variable costs at each quantity produced. The resulting changes in prices and quantities in each market is dictated by the demand and supply elasticities assumed. The EPA based these elasticities on estimates from the literature, econometric estimation, and ballpark estimates based on estimates for similar commodities.

Finally, the EPA used the information on changes in prices and quantities to calculate changes in consumer and producer surplus in the affected markets relative to the baseline. Producer surplus effects are separated into effects on producers that withdraw their products from the market, those that reformulate their products, and producers who are not subject to the regulatory requirements.

For more information, see http://nepis.epa.gov/Exe/ZyPDF.cgi/2000NW9Z.PDF?Dockey=2000NW9Z.PDF

Forest and Agricultural Sector Optimization (FASOM) Model

FASOM is a dynamic, long term economic model of the U.S. agriculture sector that maximizes total producer revenues while meeting consumer demand. The model was developed to evaluate the welfare and market impacts of environmental policies and has been used by the EPA to analyze the effects of the Renewable Fuel Standard on land allocation decisions, commodity prices and quantities, and farm income.

Using a number of inputs, FASOM determines which crops, livestock, and processed agricultural products will be produced in the U.S. In each model simulation, crops compete for price sensitive inputs such as land and labor at the regional level. The cost of these and other inputs are used to determine the price and level of production of primary commodities (e.g., field crops, livestock, and biofuel products). FASOM also estimates prices using costs associated with the processing of primary commodities into secondary products (e.g., converting livestock to meat and dairy, crushing soybeans to soybean meal and oil). FASOM does not capture short-term fluctuations (i.e., month-to-month, annual) in prices and production, as it is designed to identify long term trends.

FASOM uses supply and demand curves for 63 U.S. state and sub-state regions, though the model can also generate curves for the 11 major U.S. domestic agricultural regions. These curves are calibrated to historic price and production data. FASOM also includes detailed supply and demand data for corn, wheat, soybeans, rice and sorghum across 37 foreign regions. FASOM maintains transportation costs to all regions and then uses this information to determine U.S. exports such that prices are then equated in all markets.

For more information on how this model was used to analyze agricultural sector impacts for the Renewable Fuels Standard, see http://www.epa.gov/otaq/renewablefuels/420r07004.pdf .

Model documentation is also available at: http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/617.pdf .

<u>Economic Model for Policy Analysis – Computable General Equilibrium (EMPAX-CGE)</u>

EMPAX-CGE is structured to represent the complex interactions between consumers and producers in the real economy. To model these interactions, EMPAX-CGE maximizes household utility while simultaneously maximizing firm profits. EMPAX-CGE uses a simplified, hierarchical representation of household and firm decision-making that reduces the behavior of households and firms to a limited number of structured decisions. EMPAX-CGE aggregates the economy into 35 distinct industries with a greater level of sectoral detail among energy-intensive and manufacturing industries. EMPAX-CGE also separates the electricity industry into fossil fuel generation and non-fossil generation, which is important for assessing the impacts of policies that affect only fossil fuel-fired electricity. EMPAX-CGE models each industry separately in five different regions based on the structure of the electricity market regions as defined by the North American Electric Reliability Council.

EMPAX-CGE assumes that households have perfect foresight of future changes in policy and maximize utility over the full time horizon of the model. To adjust to future policy changes, households may alter their decisions about labor force participation and modify consumption patterns in terms of overall level of consumption and the mix of goods and services they consume. EMPAX-CGE contains four representative households in each model region, classified by income. These representative households are assumed to possess certain factors of production including labor, capital, natural resources, and land inputs to agricultural production.

The outputs generated by EMPAX-CGE include GDP, consumption, and economic welfare as measured by Hicksian equivalent variation (EV). It is important to note that EMPAX-CGE's estimation of EV captures welfare associated with market goods and services but does not capture non-market effects such as avoided pain and suffering associated with health effects incidence, improvements in visibility, and changes in service flows that derive from well-functioning ecological resources.

For more information on how EMPAX-CGE was used in *The Benefits and Costs of the Clean Air Act from 1990 to 2020* (U.S. EPA 2011a) see http://www.epa.gov/cleanairactbenefits/feb11/fullreport_rev_a.pdf.

Model documentation, source code, information about data files, and peer review comments are available at U.S. EPA (2008c) and at http://www.epa.gov/ttnecas1/EMPAXCGE.htm .

Intertemporal General Equilibrium Model (IGEM)

IGEM is an econometrically-estimated inter-temporal general equilibrium model of the United States economy that emphasizes energy and certain aspects of the environment. The model depicts growth of the economy due to capital accumulation, technical change, and population change and changes in consumption patterns due to demographic changes, price, and income effects. The model includes 35 sectors, five energy and thirty non-energy sectors. Consumers are assumed to have perfect foresight.

Capital accumulation in the model arises from the saving and investment behavior of households and firms, and provides an essential input to production and consumption. Households make choices regarding present and future consumption (i.e., saving) and the allocation of their time between labor and leisure. The model covers all aspects of long-run growth including the supply of capital, labor, imported and intermediate inputs to production; the rates and directions of exogenous and endogenous technical change for each producing sector; and the degrees of substitutability among inputs and commodities in production and final demand (consumption, investment, governments and foreign trade).

Substitution possibilities for producers and consumers are driven by model parameters that are based on observed market behavior revealed over the past 40-50 years. Specifically, IGEM is implemented econometrically, which means that the parameters governing the behavior of producers and consumers are statistically estimated using a time series dataset that is constructed specifically for this purpose. These data are based on a system of national accounts developed by Dale Jorgenson that integrates the capital accounts with the National Income Accounts. These capital accounts include an equation linking the price of investment goods to the stream of future rental flows, a link that is essential to model the dynamics of growth. This is in contrast to many other CGE models that are calibrated to the economy for one particular year.

For information on EPA"s peer review of IGEM, see
http://www.epa.gov/climatechange/EPAactivities/economics/modeling/peerreview.html .

IGEM is developed and run by Dale Jorgenson Associates for EPA. For more information on model developments, see http://www.igem.insightworks.com/ .